ANNAMACHARYA INSTITUTE OF TECHNOLOGY AND SCIENCES TIRUPATI -517520

Estd: 2007

SUBJECT: EM-I

CODE : 20APC0203

CLASS : IIB.Tech-ISEM

BRANCH : **EEE**

FACULTY NAME : **S.JAREENA& K.NEELIMA**

ACADEMIC YEAR:2023-24

UNIT-I

Electromechanical Energy Conversion

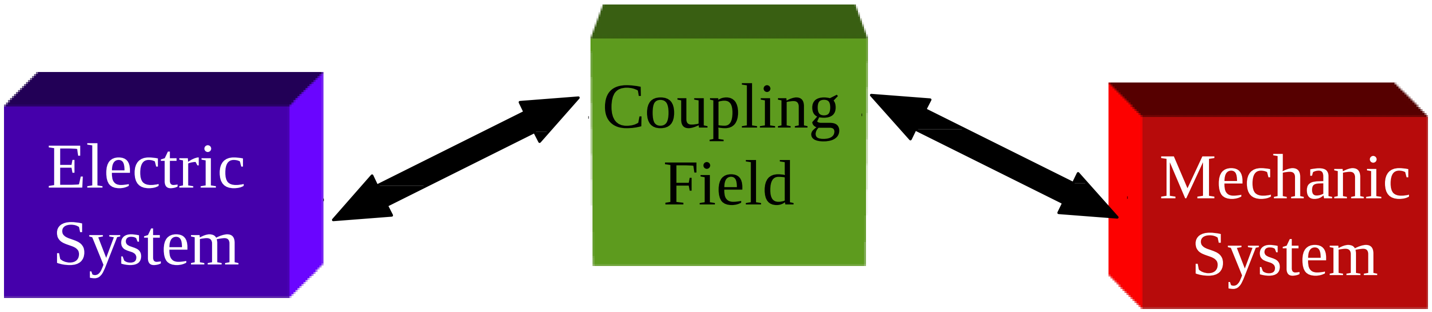
Electromechanical Energy Conversion

The electromechanical energy conversion theory allows the representation of the electromagnetic force or torque in terms of device variables, such as the currents and the displacement of the mechanical systems.

An electromechanical system consists of an electric system, a mechanical system, and a means whereby the electric and mechanical systems can interact.

Electromechanical Energy Conversion

Consider the block diagram depicted below.



W_E = W_e + W_{eL} + W_{eS}

Energy supplied by an electric source

Energy transferred to the coupling field by the electric system

Energy losses of the electric system. Basically, I^2R

Energy stored in the electric o magnetic field

Electromechanical Energy Conversion

$$W_M = W_m + W_{mL} + W_{mS}$$

- W_M: Energy supplied by a mechanical source
- W_m: Energy transferred to the coupling field from the mechanical system
- W_{mL}: Energy losses of the mechanical system
- W_{mS}: Energy stored in the moving member and compliance of the mechanical system

The energy transferred to the coupling field can be represented by

$$W_F = W_e + W_m$$

- W_F: Total energy transferred to the coupling field
- W_e: Energy transferred to the coupling field by the electric system
- W_m: Energy transferred to the coupling field from the mechanical system

$$W_F = W_f + W_{fL}$$

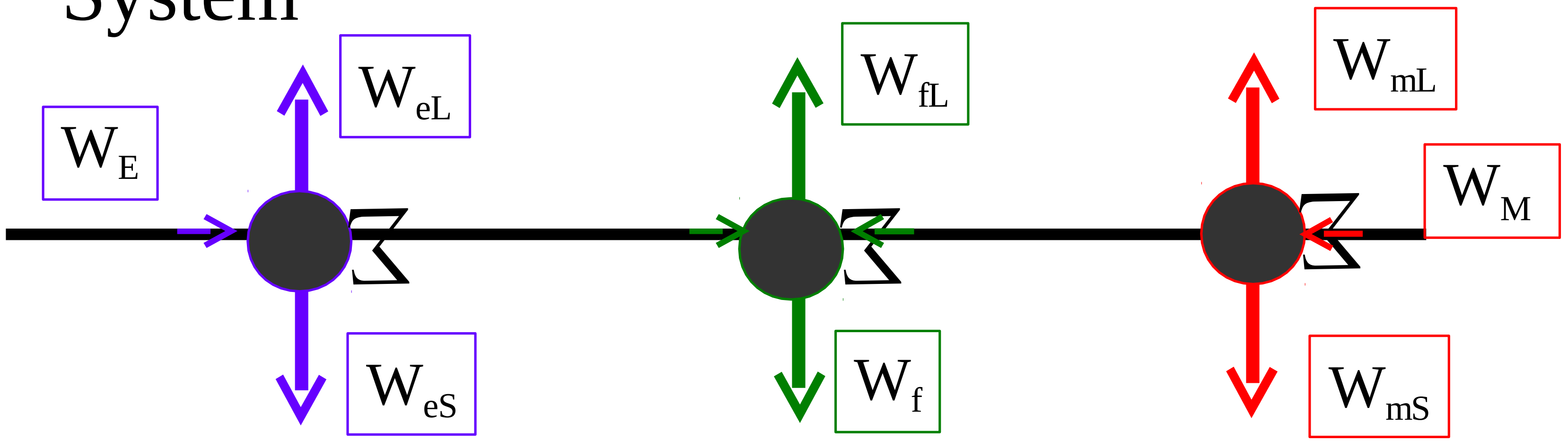
- W_f: Energy stored in the electric system
- W_{fL}: Energy dissipated as heat (I^2R)

Electromechanical Energy Conversion

The electromechanical systems obey the law of conservation of energy.

$$\mathbf{W_F = W_f \quad + \quad W_{fL} = W_e \quad + \quad W_m}$$

Energy Balance in an Electromechanical System



Electromechanical Energy Conversion

If the losses are neglected, we will obtain the following formula,

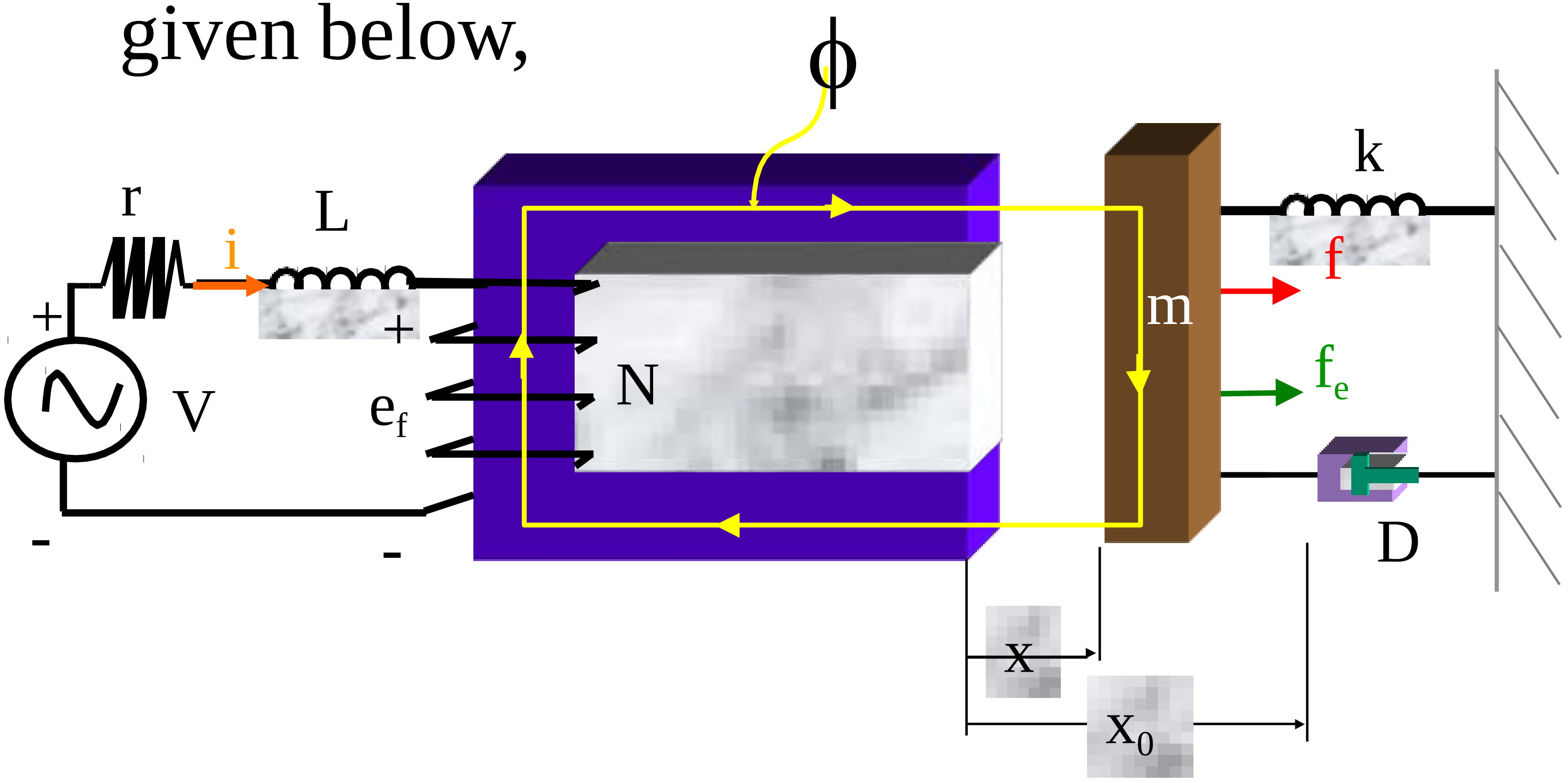
$$\mathbf{W_F = W_e + W_m}$$

Energy transferred to the coupling field by the electric system

Energy transferred to the coupling field from the mechanical system

Electromechanical Energy Conversion

Consider the electromechanical system given below,



Electromechanical Energy Conversion

The equation for the electric system is-

$$V = ri + L\frac{di}{dt} + e_f$$

The equation for the mechanical system is-

$$f = m\frac{dx^2}{dt^2} + D\frac{dx}{dt} + K(x - x_0) - fe$$

Electromechanical Energy Conversion

The total energy supplied by the electric source is -

$$W_{E}=\int V\, i\ dt = \int\left(ri + L\frac{di}{dt} + e_f \right) i\ dt$$

The equation for the mechanical system is-

$$W_M = \int f\, dx = \int f\,\frac{dx}{dt}\,dt$$

Electromechanical Energy Conversion

Substituting *f* from the equation of motion-

$$W_E = \int f\, dx = \int \left(\underbrace{m\frac{d^2x}{dt^2}}_{\substack{\text{Kinetic energy}\\ \text{stored in the mass}}} + \underbrace{D\frac{dx}{dt}}_{\substack{\text{Heat loss}\\ \text{due the friction}\\ \text{(Wall)}}} + \underbrace{K(x - x_0)}_{\substack{\text{Potential Energy}\\ \text{stored in the spring}}} - \underbrace{fe}_{\substack{\text{Total energy}\\ \text{transferred to the}\\ \text{coupling field}\\ \text{from the}\\ \text{mechanical}\\ \text{system}}} \right) dx$$

Electromechanical Energy Conversion

$$W_M = -\int f_e dx$$

$$*\,Recall$$

$$W_f = We + W_M$$

$$W_f = \int e_f i dt - \int f_e dx$$

$$dW_f = e_f i dt - f_e dx$$

Electromechanical Energy Conversion

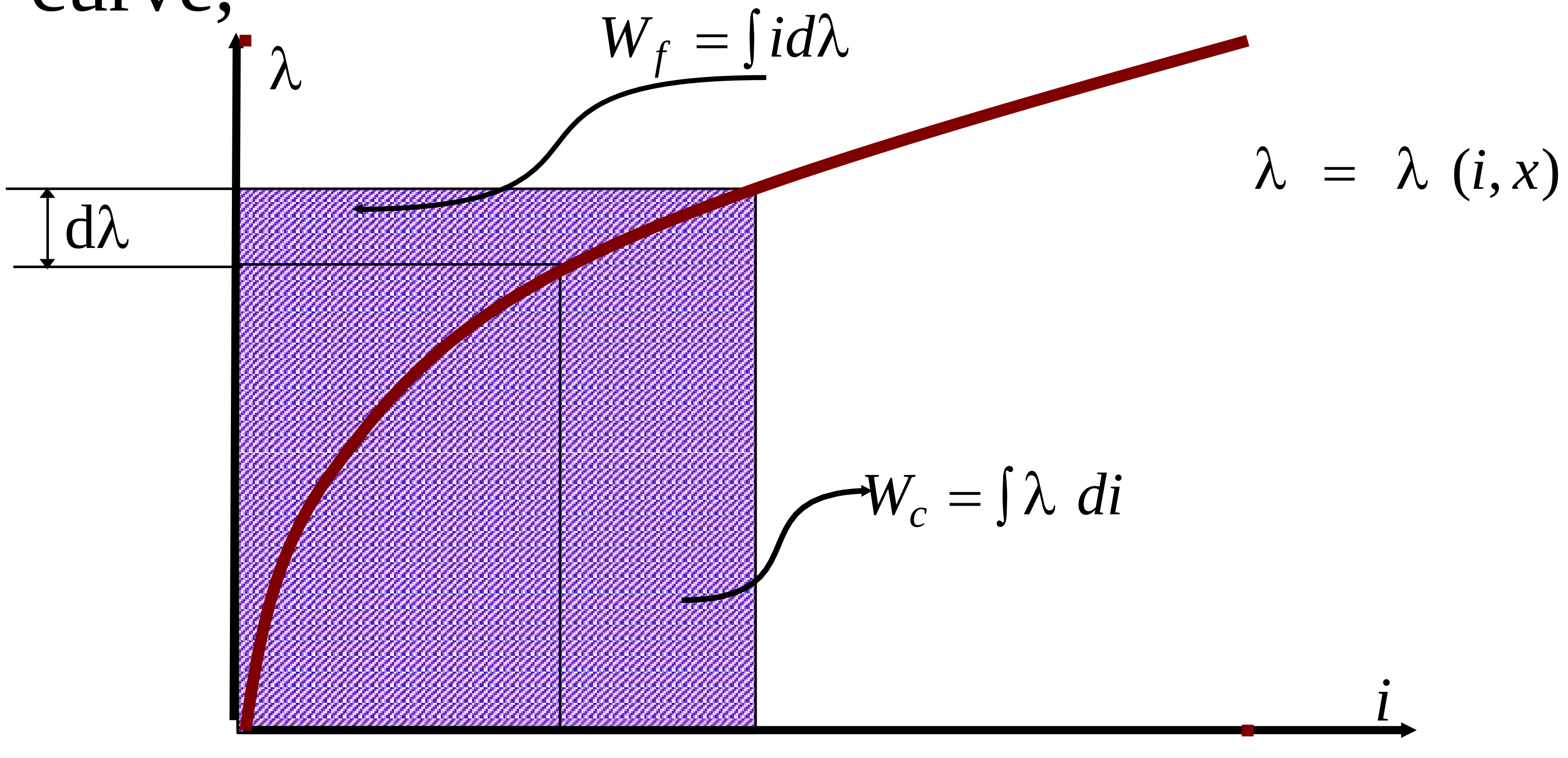
If dx=0 is assumed, then

$$W_f = W_E = \int e_f i dt = \int \frac{d\lambda}{dt} \; i \; dt$$

$$\boxed{W_f = \int i d\lambda \Big|_{dx=0}}$$

Electromechanical Energy Conversion

Recalling the normalized magnetization curve,



Electromechanical Energy Conversion

$$\lambda = \lambda(i, x)$$

$$d\lambda = \frac{\partial \lambda(i, x)}{\partial i} di + \frac{\partial \lambda(i, x)}{\partial x} dx$$

$$W_f = \int \frac{\partial \lambda(i, x)}{\partial i} i \, di \Big|_{dx=0}$$

Electromechanical Energy Conversion

$$i = i(\lambda \ , x)$$

$$di = \frac{\partial i(\lambda \ , x)}{\partial \lambda} d\lambda \ + \frac{\partial i(\lambda \ , x)}{\partial x} dx$$

$$W_c = \int \lambda \ \ di = \int \lambda \left(\frac{\partial i(\lambda \ , x)}{\partial \lambda} d\lambda \ \right)\Bigg|_{dx=0}$$

Electromechanical Energy Conversion

From the previous relationship, it can be shown that for one coil,

$$W_f = \int_0^{i^*} i \quad d\lambda \qquad\qquad \lambda = L(x)\, i$$

$$W_f = \int_0^{i^*} i\, L(x)\, di$$

For a general case,

$$W_f = \int \sum_{j=1} i_j\, d\lambda_j \Big|_{dx=0}$$

Electromechanical Energy Conversion

For two coupled coils,

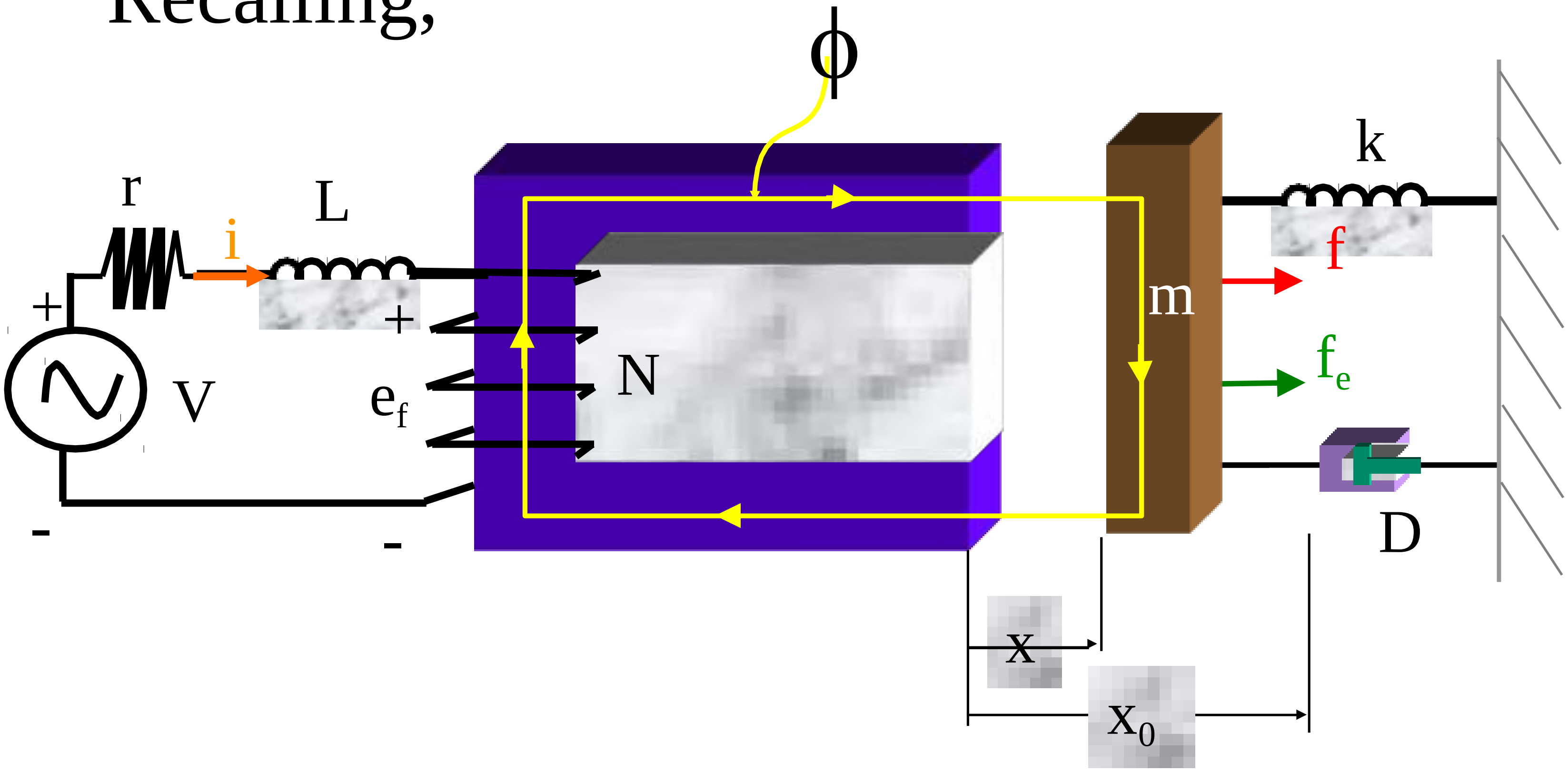
$$W_f = \frac{1}{2} L_{11} i^2{}_1 + L_{12} i_1 i_2 + \frac{1}{2} L_{22} i^2{}_2$$

For the general case with n-coupled coils,

$$W_f = \frac{1}{2} \sum_{p=1}^{n} \sum_{q=1}^{n} L_{pq} i_p i_q$$

Electromagnetic Force

Recalling,



Electromagnetic Force

- $W_f = \int e_f\, i\, dt - \int f_e\, dx \quad f_e dx = dW_e - dW_f$

$$W_f = We + W_M$$

$$e_f = \frac{d\lambda}{dt}$$

Electromagnetic Force

$$dW_e = e_f i dt = \frac{d\lambda}{dt} i \; dt = i \; d\lambda$$

$$f_e dx = i \; d\lambda - dW_f$$

$$d\lambda \quad = \frac{\partial\lambda \;(i,x)}{\partial i} di + \frac{\partial\lambda \;(i,x)}{\partial x} dx$$

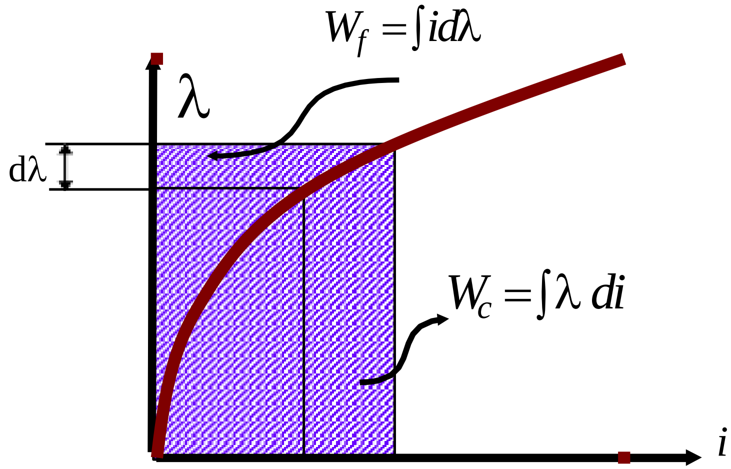
$$dW_f \quad = \frac{\partial W_f \,(i,x)}{\partial i} di + \frac{\partial W_f \,(i,x)}{\partial x} dx$$

Substituting for $d\lambda$ and dW_f in $f_e dx = id\,\lambda \;\; dW_{f,}$ it can be shown

$$f_e(i,x) = i\,\frac{\partial\lambda}{\partial x} - dW_f$$

Electromagnetic Force

Recall,



$$W_c = i\lambda - W_f$$

$$\frac{\partial W_c}{\partial x} = i\frac{\partial \lambda}{\partial x} - \frac{\partial W_f}{\partial x}$$

$$f_e(i,x) = i\frac{\partial \lambda}{\partial x} - \frac{\partial W_f}{\partial x}$$

Electromagnetic Force

$$\lambda \quad i = W_f + W_c \qquad\qquad W_f = \lambda \quad i - W_c$$

$$f_e(i,x) = i\,\frac{\partial \lambda}{\partial x} - \frac{\partial W_f}{\partial x}$$

$$f_e(i,x) = i\,\frac{\partial \lambda}{\partial x} - i\,\frac{\partial \lambda}{\partial x} - \left(-\frac{\partial W_c}{\partial x} \right)$$

$$\boxed{f_e(i,x) = +\frac{\partial W_c}{\partial x}}$$

UNIT-II

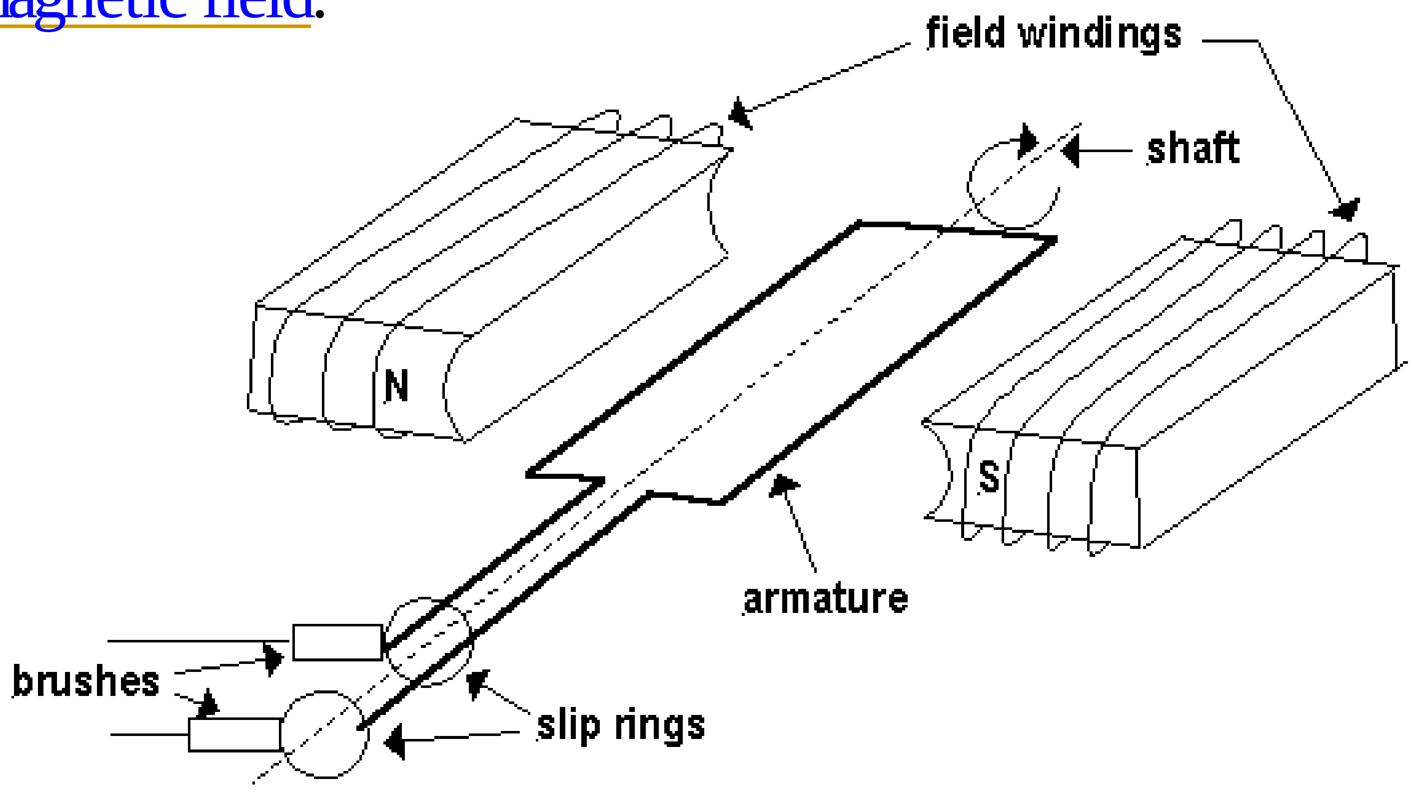
DC GENERATORS

DC Generator

- *An Electrical Generator is a machine which converts mechanical energy (or Power) into Electrical energy (or Power).*
- There are two types of generators, one is ac generator and other is dc generator.
- Whatever may be the types of generators, it always converts mechanical power to electrical power.
- An ac generator produces alternating power. A DC generator produces direct power.
- Both of these generators produce electrical power, based on same fundamental principle of Faraday's law of electromagnetic induction.
- According to these law, when an conductor moves in a magnetic field it cuts magnetic lines force, due to which an emf is induced in the conductor. The magnitude of this induced emf depends upon the rate of change of flux (magnetic line force) linkage with the conductor. This emf will cause an current to flow if the conductor circuit is closed.

DC Generator

- Hence the most basic tow essential parts of a generator are a magnetic field and conductors which move inside that magnetic field.



DC Generator

- The **armature** – a coil wound around a metal core and mounted between the poles of an electromagnet.
- The **electromagnet** consisting of an iron core surrounded by a set of coils called the **field windings**. A steady current flows through these coils to produce the required magnetic field.
- The **slip rings** – each end of the armature coil is connected to a metal ring. These rings are mounted on the armature shaft but are insulated from it and from each other.
- The **graphite brushes** – these connect the slip rings to an external circuit and conduct the current induced in the armature coil to the external circuit.
- The armature is **mechanically driven** by a steam turbine or a belt & pulley system or by hydroelectric means. As the armature turns, one side moves up through the magnetic field and the other side moves downwards.

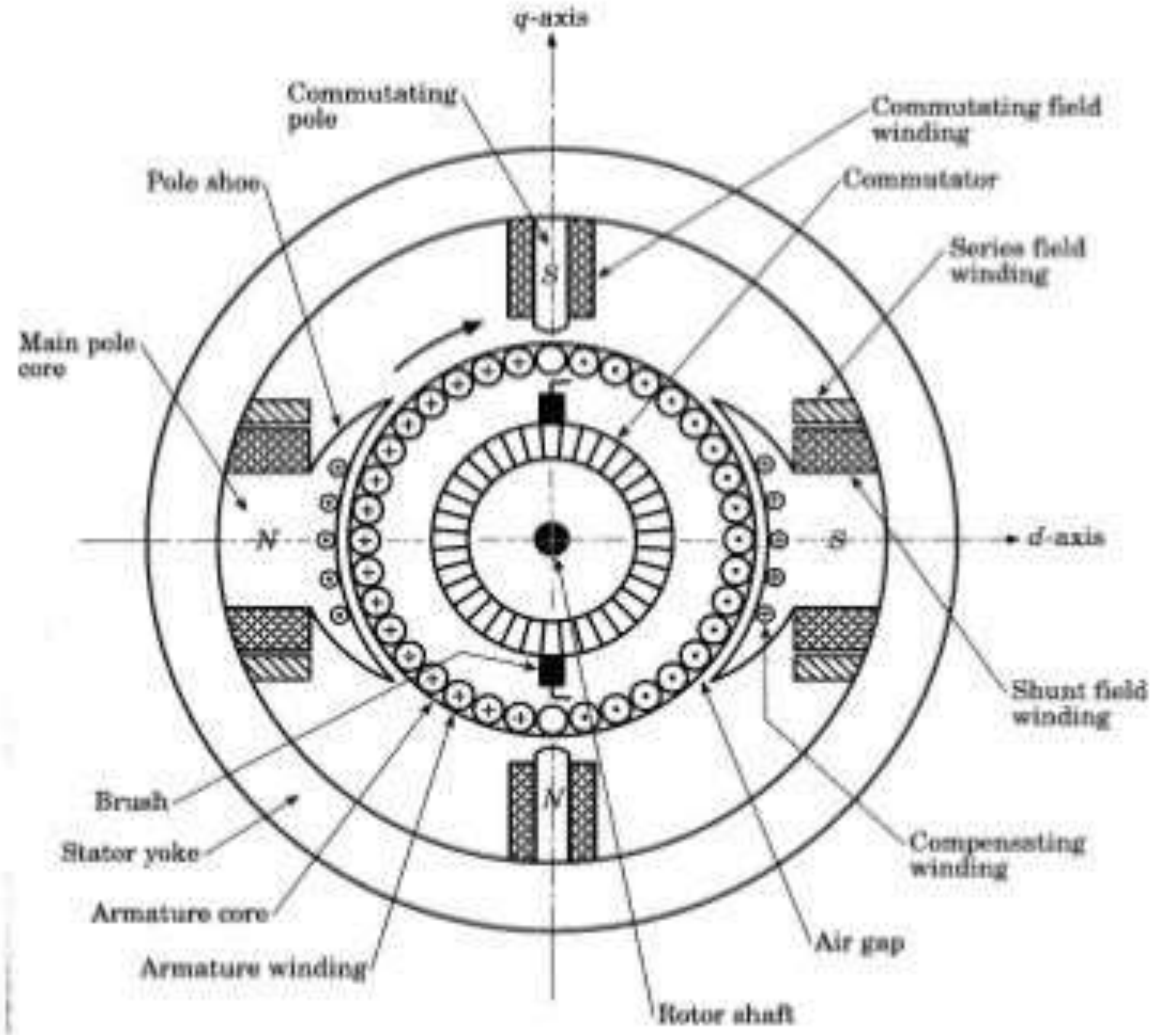
DC Generator

- The coil thus experiences a change of magnetic flux with time. The result is that an emf is induced in one direction in one side of the coil and in the other direction in the other side of the coil.
- Thus, these emf's act in the same sense around the coil. The ends of the coil are connected to slip rings against which rest graphite brushes. When these brushes are connected across an external circuit, the induced emf produces an electric current.
- Each time the coil passes through the position where its plane is perpendicular to the magnetic field lines, the direction of the emf in the coil is reversed. Hence an **alternating current** is produced at a frequency equal to the number of revolutions per second of the armature.

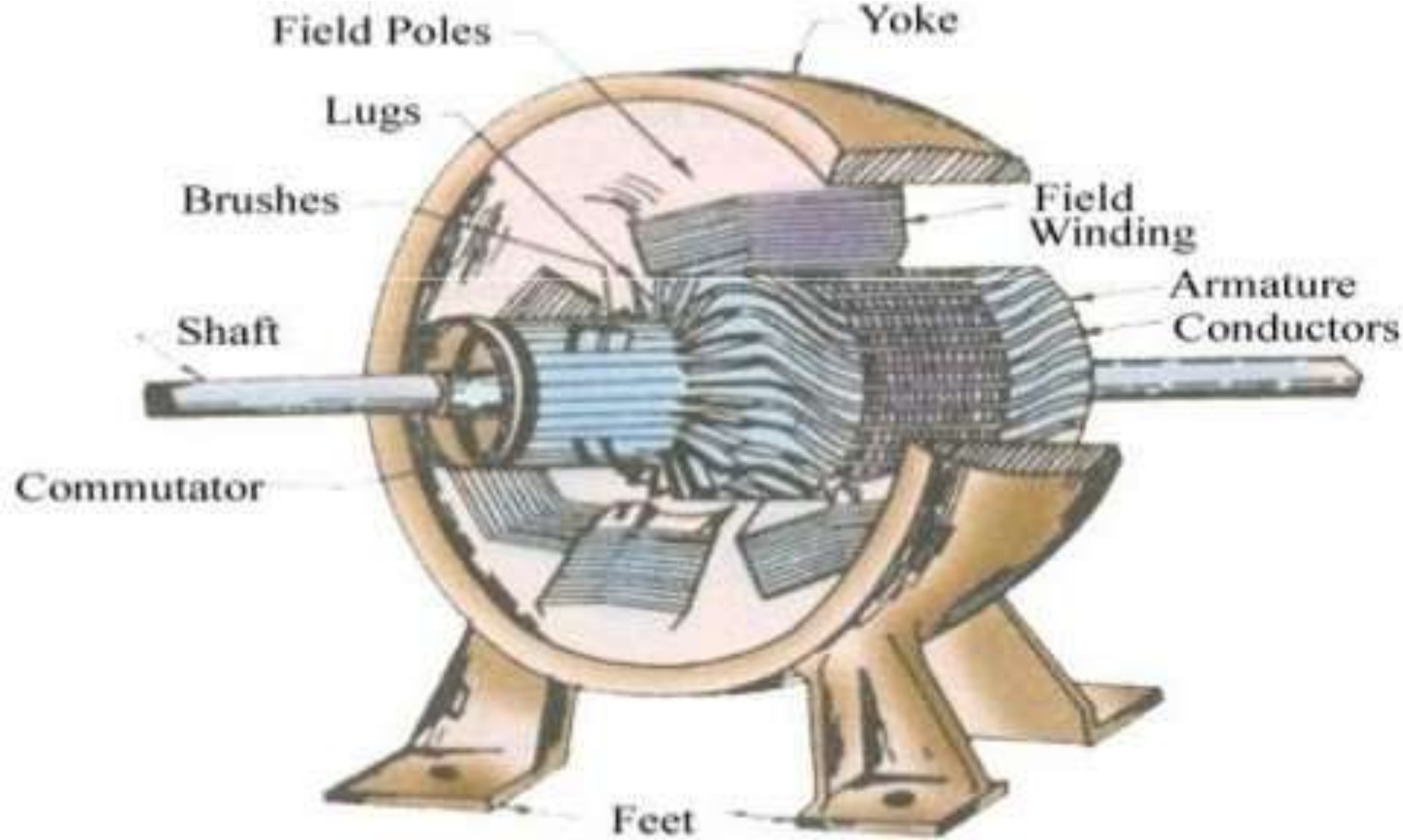
DC Generator

- An **alternating current generator** may be converted to a **direct current generator** in a couple of ways:
- By using a **split ring commutator** instead of slip rings. The split ring commutator is mounted on the armature shaft but is insulated from it. The commutator reverses the connections of the coil to the external circuit each time the current in the coil reverses. Thus, a DC output is achieved from the AC generator.
- By using a **bridge rectifier circuit**. This is an arrangement of electronic components **(diodes)** that converts the AC output from the generator to a DC output.
- Note that in an **electric current generator, mechanical energy is transformed into electrical energy**. In an **electric current motor, electrical energy is transformed into mechanical energy**.

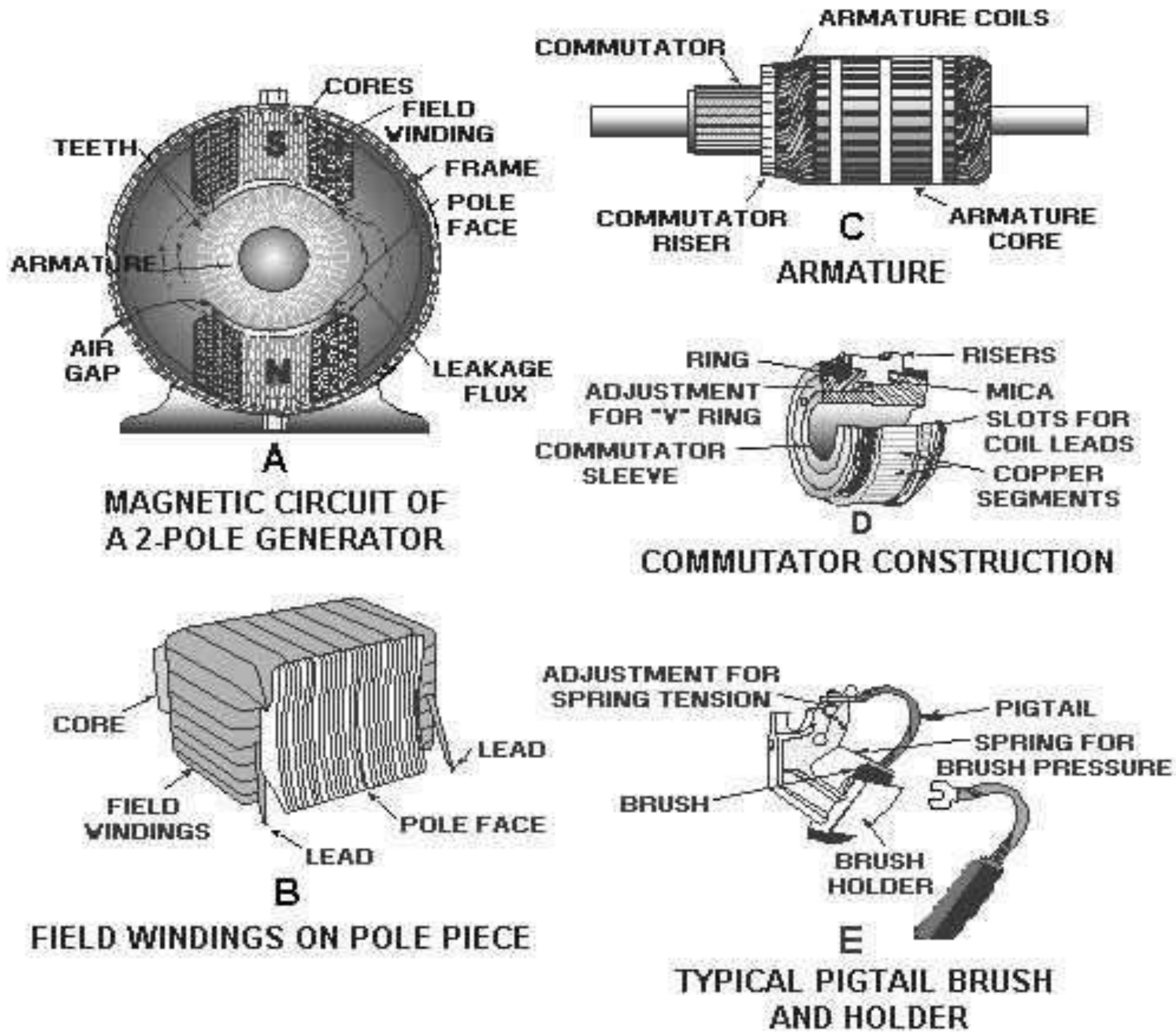
DC Generator



DC Generator

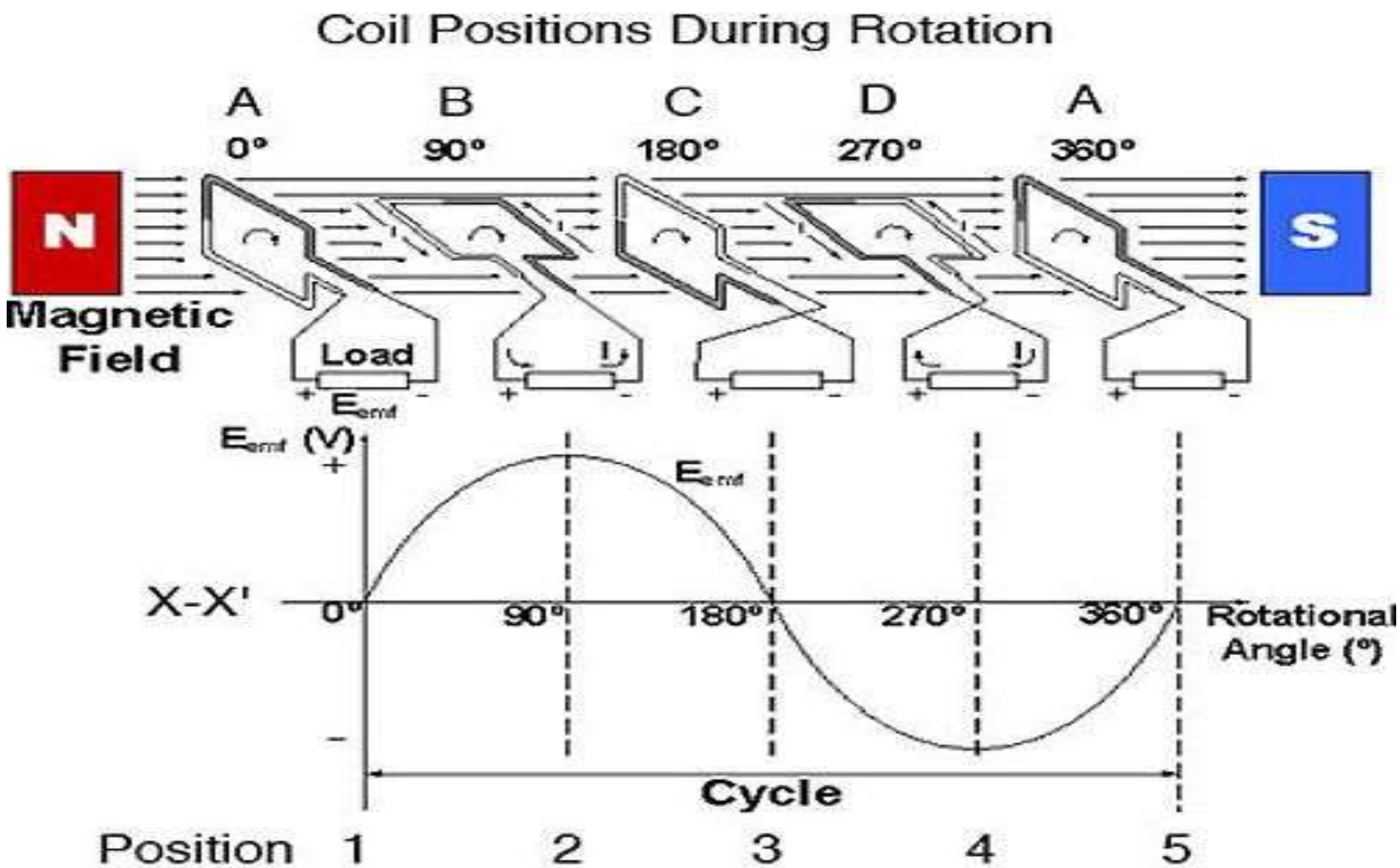


DC Generator

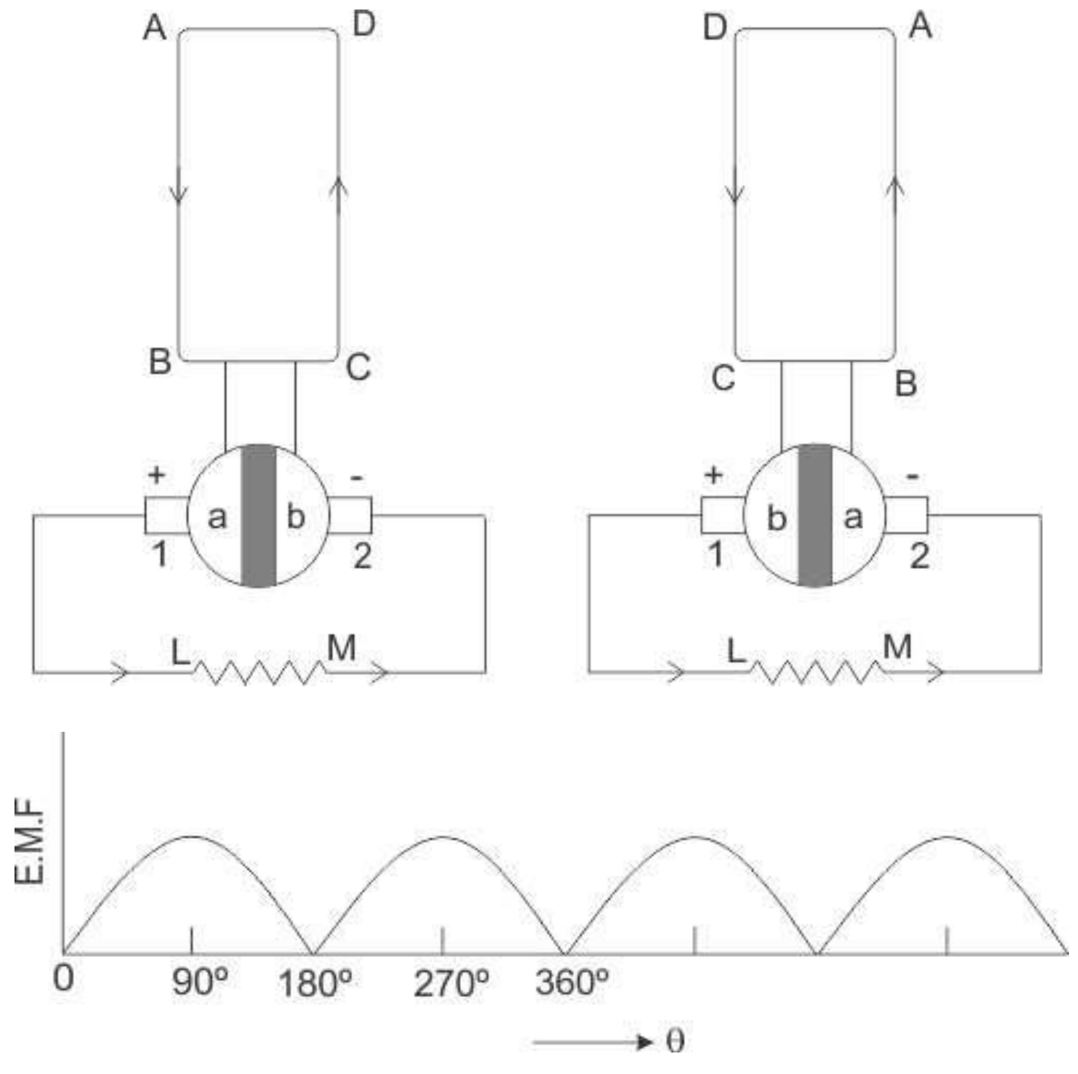


DC Generator

DC Generator

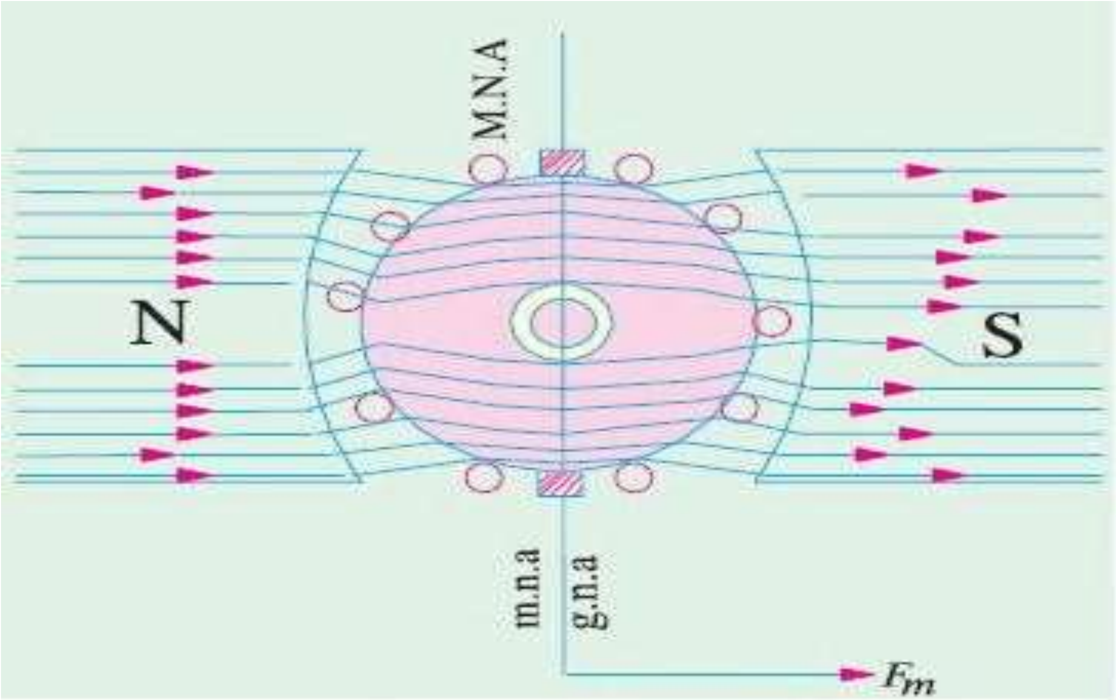


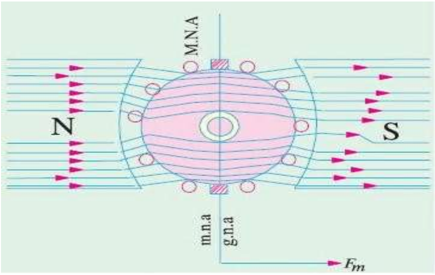
DC Generator



Armature Reaction

- The effect of magnetic field set up by armature current on the distribution of flux under main poles of a generator. The armature magnetic field has two effects:
- It demagnetises or weakens the main flux and
- It cross-magnetises or distorts it.





Armature Reaction

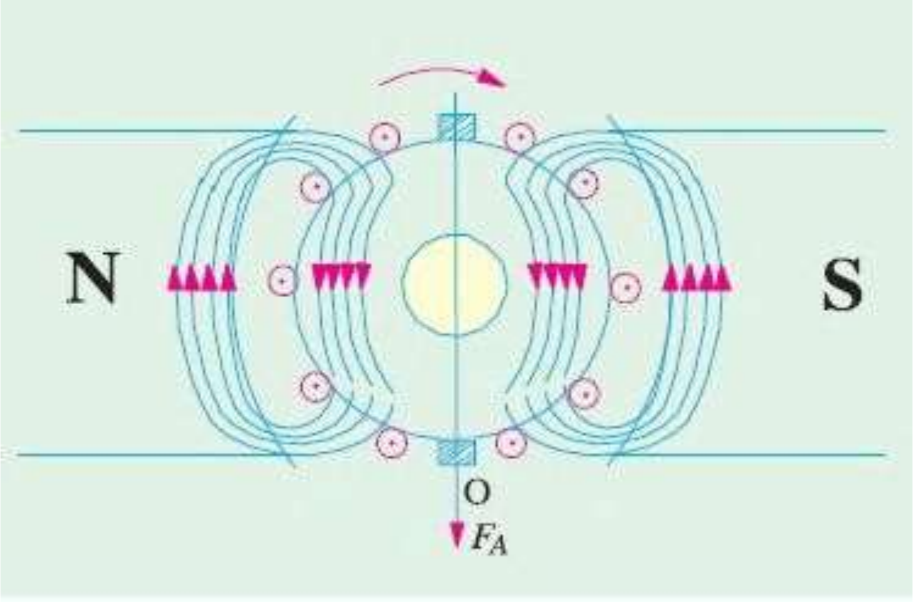
- Fig above shows the flux distribution of a bipolar generator when there is no current in the armature conductors.
- The brushes are touching the armature conductors directly, although in practice, they touch commutator segments, it is seen that:
- (a) the flux is distributed symmetrically with respect to the polar axis, which is the line joining the centres of NS poles.
- (b) The magnetic neutral axis (M.N.A.) coincides with the geometrical neutral axis (G.N.A.).
- *Magnetic neutral axis may be defined as the axis along which no emf is produced in the armature conductors because they move parallel to the lines of flux.*

OR

- *M.N.A. is the axis which is perpendicular to the flux passing through the armature.*

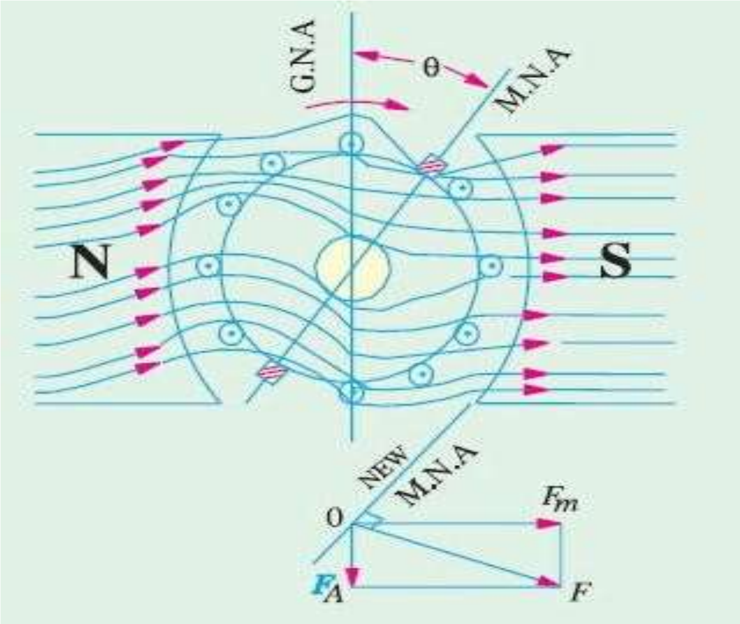
Armature Reaction

- Brushes are always placed along M.N.A. Hence, M.N.A. is also called ‘axis of commutation’ because reversal of current in armature conductors takes place across this axis.
- Vector OFm which represents, both magnitude and direction, the mmf of producing the main flux.
- Fig below shows the field (or flux) set up by the armature conductors alone when carrying current, the field coils being unexcited. The current direction is downwards in conductors under N-pole and upwards in those under S-pole.



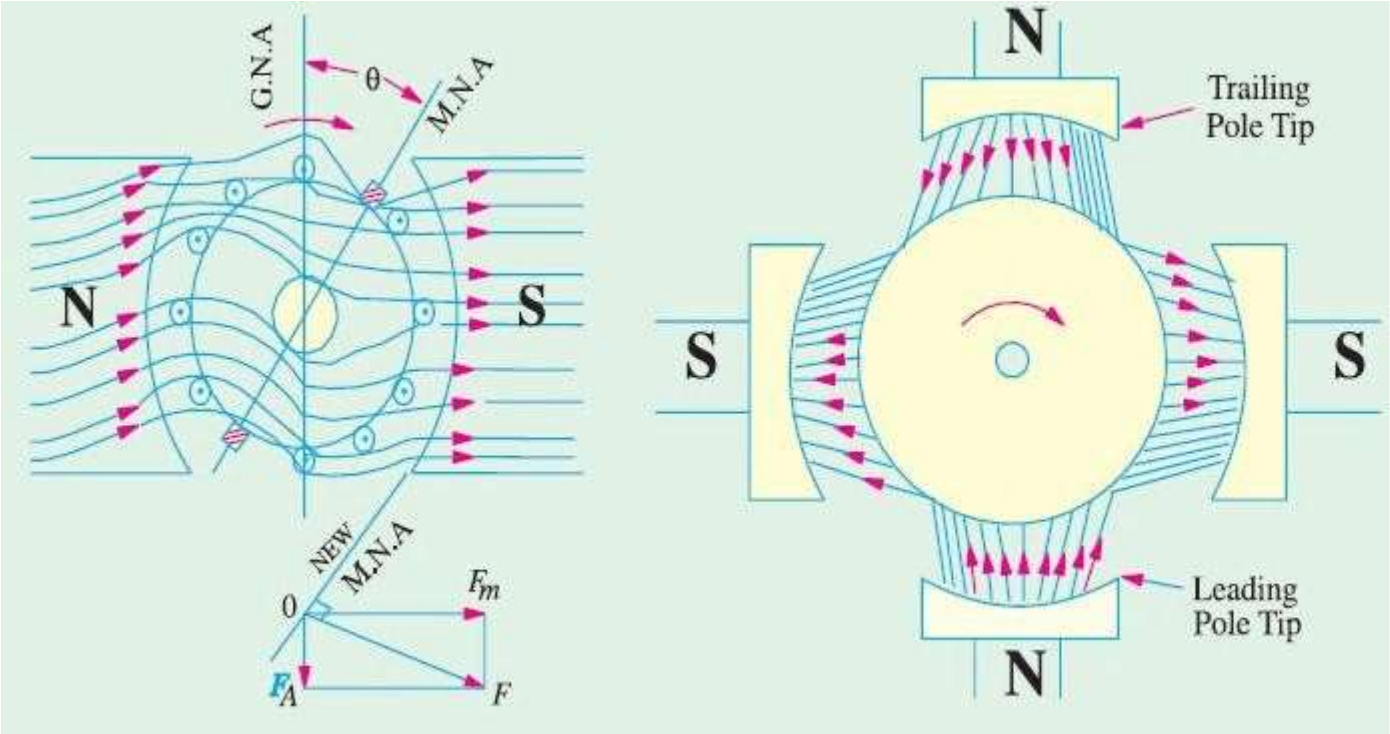
Armature Reaction

- The armature mmf (depending on the strength of the armature current) is shown separately both in magnitude and direction by the vector OFA. Under actual load conditions, the two mmf exist simultaneously in the generator as shown in figure below.
- It is seen that the flux through the armature is no longer uniform and symmetrical about the pole axis, rather it has been distorted.

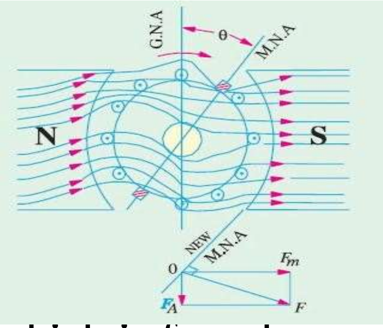


Armature Reaction

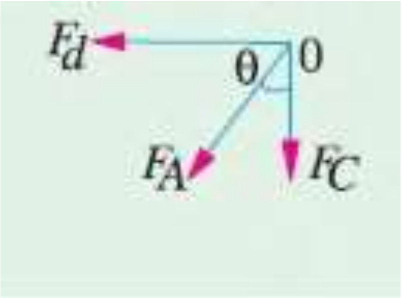
- The flux is seen to be crowded at the trailing pole tips but weakened or thinned out at the leading pole tips (*the pole tip which is first met during rotation by armature conductors is known as the leading pole tip and the other as trailing pole tip*).
- The strengthening and weakening of flux is separately shown for a four-pole machine in Fig.



Armature Reaction

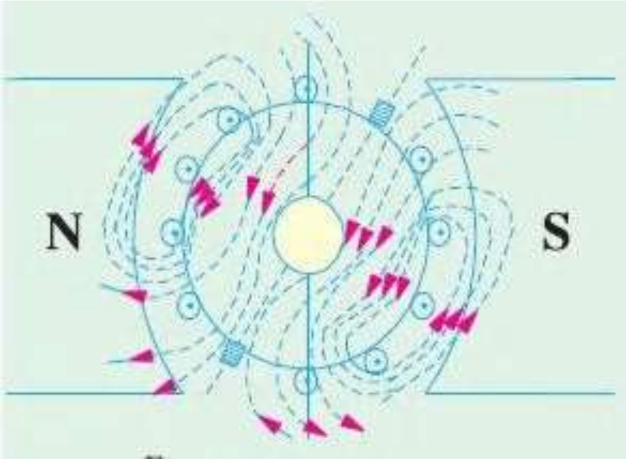


- In is shown the resultant mmf OF (The new position of M.N.A.) which is found by vectorially combining OFm and OFA. And the new position of M.N.A which is always perpendicular to the resultant mmf vector OF, is also shown in the figure. 0
- With the shift of M.N.A., say through an angle θ brushes are also shifted so as to lie along the new position of M.N.A. Due to this brush shift , the armature conductors and hence armature current is redistributed.
- All conductors to the left of new position of M.N.A. but between the two brushes, carry current downwards and those to the right carry current upwards. The armature mmf is found to lie in the direction of the new position of M.N.A. (or brush axis). The armature mmf is now represented by the vector OFA.



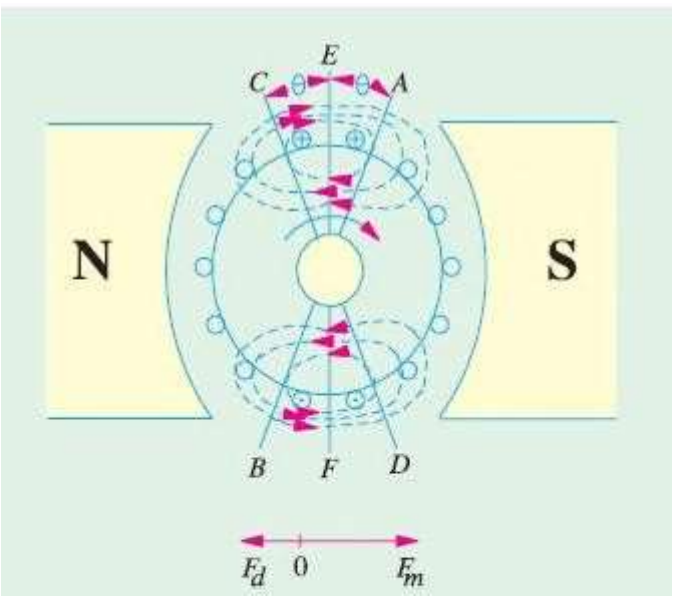
Armature Reaction

- OFA can now be resolved into two rectangular components, OFd parallel to polar axis and OFC perpendicular to this axis.
- We find that: (i) Component OFC is at right angles to the vector OFm representing the main mmf It produces distortion in the main field and is hence called the cross-magnetising or distorting component of the armature reaction.
- (ii) The component OFd is in direct opposition of OFm which represents the main mmf It exerts a demagnetising influence on the main pole flux. Hence, it is called the demagnetising or weakening component of the armature reaction.
- It should be noted that both distorting and demagnetising effects will increase with increase in the armature current.



Armature Reaction

- **Demagnetising and Cross-magnetising Conductors:**
- All conductors lying within angles AOC = BOD = 2 θ at the top and bottom of the armature, are carrying current in such a direction as to send the flux through the armature from right to left. It is these conductors which act in direct opposition to the main field and are hence called the demagnetising armature conductors.



- Now consider the remaining armature conductors lying between angles AOD and COB.
- These conductors carry current in such a direction as to produce a flux at right angles to the main flux.
- This results in distortion of the main field. Hence, these conductors are known as cross-magnetising conductors and constitute distorting ampere-conductors.

Armature Reaction

- Since armature demagnetising ampere-turns are neutralized by adding extra ampereturns to the main field winding, it is essential to calculate their number. But before proceeding further, it should be remembered that the number of turns is equal to half the number of conductors because two conductors-constitute one turn.
- Let Z = total number of armature conductors
- I = current in each armature conductor
- = Ia/2 … for simplex wave winding
- = Ia/P … for simplex lap winding
- = forward lead in mechanical or geometrical or angular degrees.
- Total number of armature conductors in angles AOC and BOD is $\frac{4\theta_m}{360} \times Z$

Armature Reaction

$\therefore$ Total number of turns in these angles $= \frac{2\theta_m}{360} \times Z$

$\therefore$ Demagnetising amp – turns per pair of pole $= \frac{2\theta_m}{360} \times ZI$ $\therefore$ AT_d per pole $= \frac{\theta_m}{360} \times ZI$

The conductors lying between angles AOD and BOC constitute what are known as distorting or cross-magnetising conductors. Their number is found as under:

Total armature-conductors/pole both cross and demagnetising = Z / P

$\therefore$ Corss-magnetising conductors/pole $= \frac{Z}{P} - Z \times \frac{2\theta_m}{360} = Z\left(\frac{1}{p} - \frac{2\theta_m}{360}\right)$

$\therefore$ Cross-magnetising amp-conductors/pole $= ZI\left(\frac{1}{p} - \frac{2\theta_m}{360}\right)$

$\therefore$ Corss-magnetising amp-turns/pole $= ZI\left(\frac{1}{2p} - \frac{\theta_m}{360}\right)$

$\therefore$ ATc/pole $= ZI\left(\frac{1}{2p} - \frac{\theta_m}{360}\right)$

Armature Reaction

For neutralizing the demagnetising effect of armature-reaction, an extra number of turns may be put on each pole.

No. of extra turns/pole $= \frac{AT_d}{I_f}$ I_f –field current

If the leakage coefficient λ is given, then multiply each of the above expressions by it. If lead angle is given in electrical degrees, it should be converted into mechanical degrees by the following relation: $\theta_m = \frac{\theta_e}{p/2} = \frac{2\theta_e}{p}$

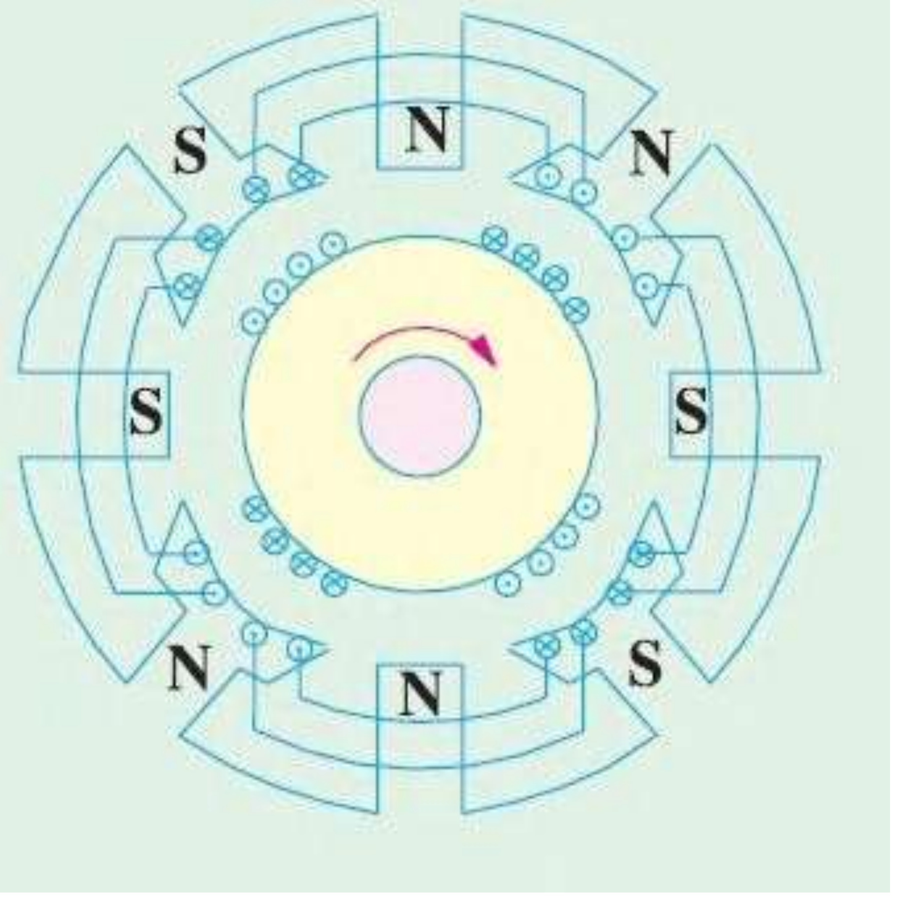
Armature Reaction

Compensating Windings:

- These are used for large direct current machines which are subjected to large fluctuations in load i.e. rolling mill motors and turbo-generators etc.
- Their function is to neutralize the cross magnetizing effect of armature reaction. In the absence of compensating windings, the flux will be suddenly shifting backward and forward with every change in load.
- This shifting of flux will induce statically induced emf in the armature coils. The magnitude of this emf will depend upon the rapidity of changes in load and the amount of change. It may be so high as to strike an the consecutive commutator segments across the top of the mica sheets separating them.
- This may further develop into a flashover around the whole commutator thereby short-circuiting the whole armature.

Armature Reaction

- These windings are embedded in slots in the pole shoes and are connected in series with armature in such a way that the current in them flows in opposite direction to that flowing in armature conductors directly below the pole shoes. arc between .



Armature Reaction

Compensating winding must provide sufficient m.m.f so as to counterbalance the armature mmf Let

Zc = No. of compensating conductos/pole face

Za = No. of active armature conductors/pole,

Ia = Total armature current

Ia/A = current of armature conductor

∴ ZcIa = Za (Ia/A) or Zc = Za/A

No. of armature conductors/pole = Z/P

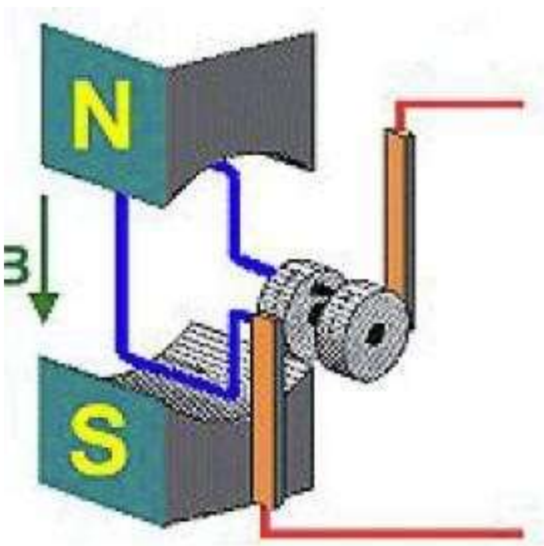
No. of armature turns/pole = Z/2P

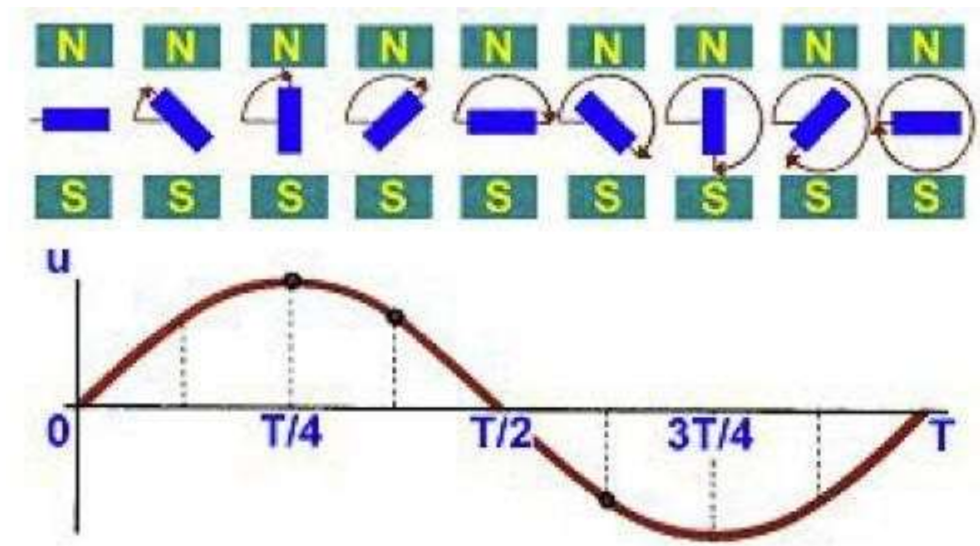
∴ No. of armature-turns immediately under one pole $= \frac{Z}{2P} \times \frac{pole\ arc}{pole\ pitch} = 0.7 \times \frac{Z}{2p}$ (apprixamatelly)

∴ No. of armature amp-turns/pole for compensating winding $= 0.7 \times \frac{Z}{2p} = 0.7 \times$ armature amp-turns/pole

Commutation

- **Commutation:** the currents induced in armature conductors of a d.c. generator are alternating. These currents flow in one direction when armature conductors are under N-pole and in the opposite direction when they are under S-pole.

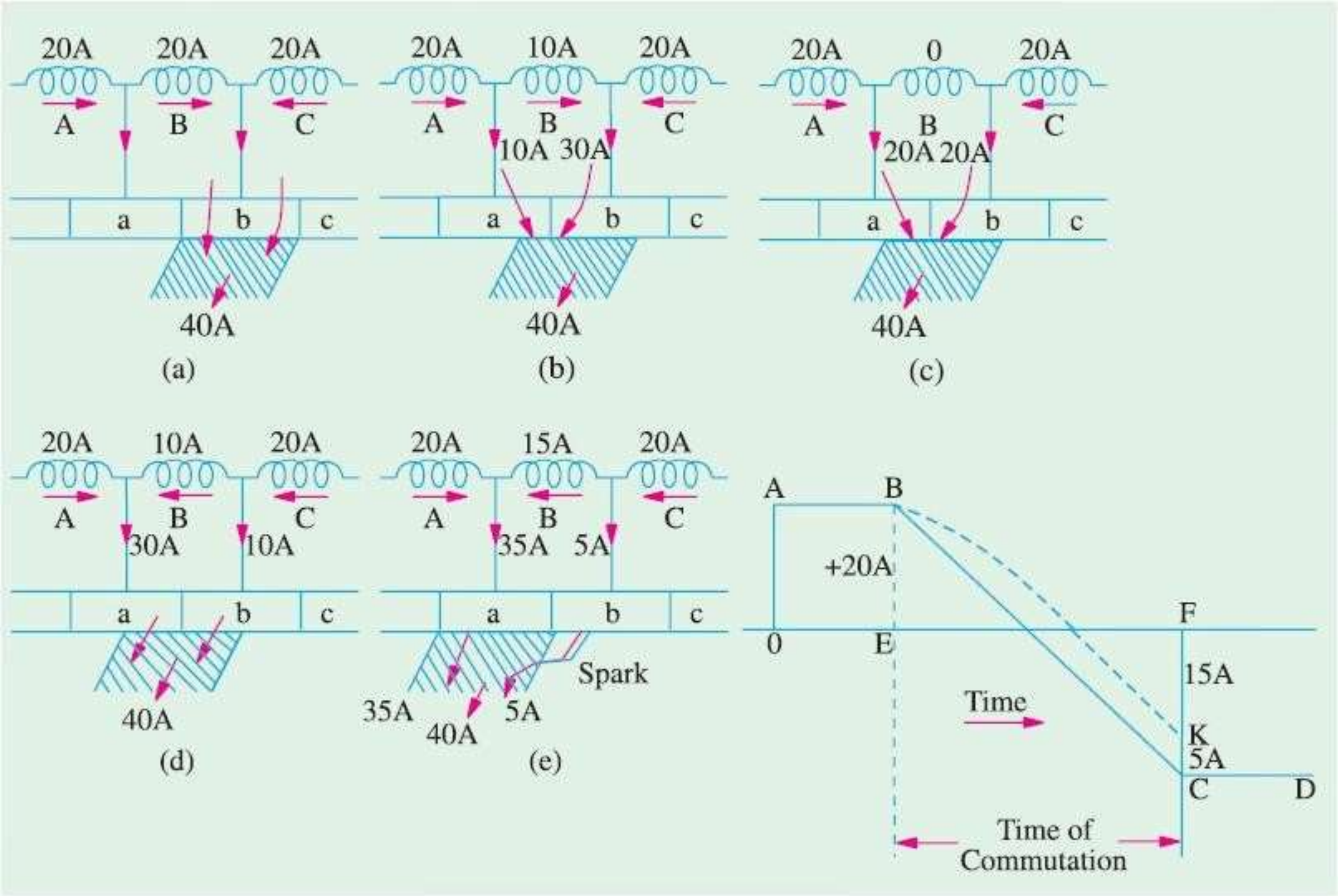




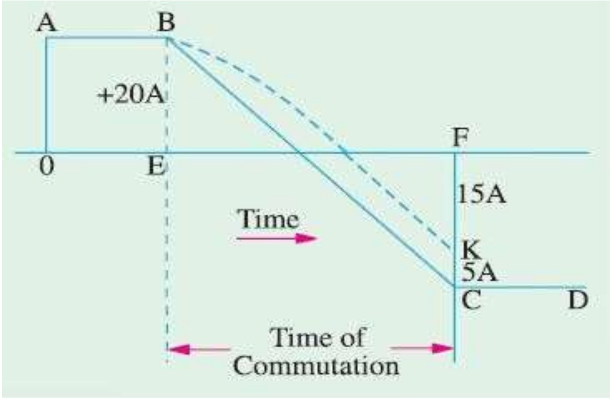
Commutation

- As conductors pass out of the influence of a N-pole and enter that of S-pole, the current in them is reversed. This reversal of current takes place along magnetic neutral axis or brush axis i.e. when the brush spans and hence short-circuits that particular coil undergoing reversal of current through it.
- *This process by which current in the short-circuited coil is reversed while it crosses the M.N.A. is called commutation.*
- The brief period during which coil remains short-circuited is known as commutation period Tc. If the current reversal i.e. the change from + I to zero and then to −I is completed by the end of short circuit or commutation period, then the commutation is ideal. If current reversal is not complete by that time, then sparking is produced between the brush and the commutator which results in progressive damage to both. The brush width is equal to the width of one commutator segment and one mica insulation.

Commutation



Commutation



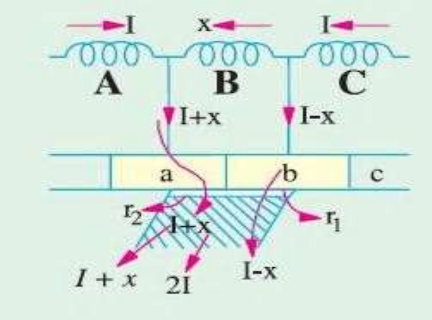
- For ideal commutation, current through it should have reversed but it is carrying 15 A only instead of 20 A.
- If the current varies at a uniform rate i.e. if BC is a straight line, then it is referred to as linear commutation.
- However, due to the production of self-induced emf in the coil the variations follow the dotted curve. It is seen that, in that case, current in coil B has reached only a value of KF = 15 A in the reversed direction, hence the difference of 5 A (20-15 A) passes as a spark.
- So, we conclude that sparking at the brushes, which results in poor commutation is due to the inability of the current in the short-circuited coil to reverse completely by the end of short-circuit period (which is usually of the order of 1/ 500 second).

Commutation

- The main cause which retards or delays this quick reversal is the production of self-induced emf in the coil undergoing commutation.
- It may be pointed out that the coil possesses appreciable amount of self inductance because it lies embedded in the armature which is built up of a material of high magnetic permeability. This self-induced emf is known as reactance voltage.
- **Method of Improving Commutation :**

1. Resistance Commutation
2. EMF Commutation
3. Inter Pole of Compole

Resistance Commutation



- This method of improving commutation consists of replacing low-resistance Cu brushes by comparatively high-resistance carbon brushes. When current I from coil C reaches the commutator segment b, it has two parallel paths open to it. The first part is straight from bar ‘b’ to the brush and the other parallel path is via the short-circuited coil B to bar ‘a’ and then to the brush. If the Cu brushes are used, then there is no inducement for the current to follow the second longer path, it would preferably follow the first path.
- But when carbon brushes having high resistance are used, then current I coming from C will prefer to pass through the second path. The additional advantages of carbon brushes are that
- (i) they are to some degree self lubricating and polish the commutator and
- (ii) should sparking occur, they would damage the commutator less than when Cu brushes are used.

Resistance Commutation

- But some of their minor disadvantages are:
- (i) Due to their high contact resistance (which is beneficial to spark-less commutation) a loss of approximately 2 volt is caused. Hence, they are not much suitable for small machines where this voltage forms an appreciable percentage loss.
- (ii) Owing to this large loss, the commutator has to be made some what larger than with Cu brushes in order to dissipate heat efficiently without greater rise of temperature.
- (iii) because of their lower current density (about 7-8 A/cm^2 as compared to 25-30 A/cm^2 for Cu brushes) they need larger brush holders.

EMF Commutation

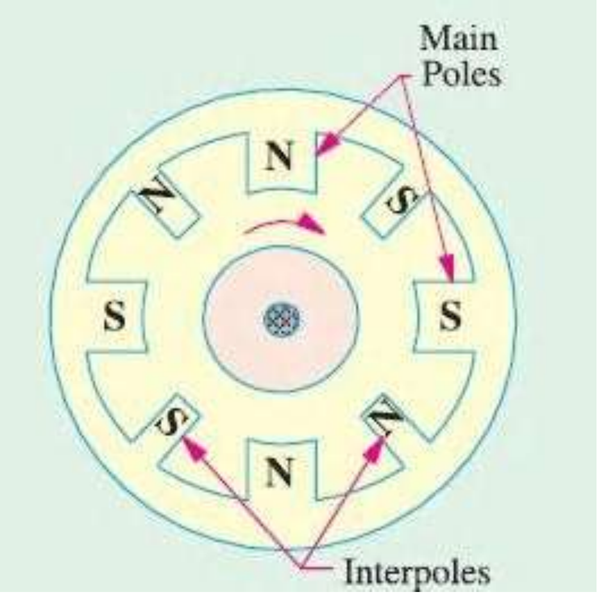
- In this method, arrangement is made to neutralize the reactance voltage by producing a reversing emf in the short-circuited coil under commutation.
- This reversing emf, as the name shows, is an emf in opposition to the reactance voltage and if its value is made equal to the latter, it will completely wipe it off, thereby producing quick reversal of current in the short-circuited coil which will result in spark-less commutation.
- The reversing emf may be produced in two ways:
- (i) either by giving the brushes a forward lead sufficient enough to bring the short-circuited coil under the influence of next pole of opposite polarity or
- (ii) by using interpoles. The first method was used in the early machines but has now been abandoned due to many other difficulties it brings along with.

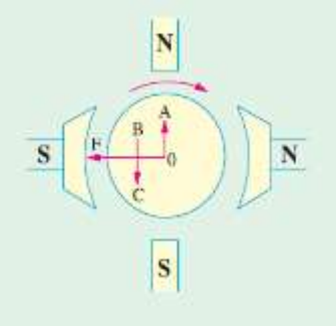
Interpole of Compoles

- These are small poles fixed to the yoke and spaced in between the main poles. They are wound with comparatively few heavy gauge Cu wire turns and are connected in series with the armature so that they carry full armature current.
- Their polarity, in the case of a generator, is the same as that of the main pole ahead in the direction of rotation.The function of interpoles is two-fold:
- (i) As their polarity is the same as that of the main pole ahead, they induce an emf in the coil (under commutation) which helps the reversal of current. The emf induced by the compoles is known as commutating or reversing emf.
- The commutating emf neutralizes the reactance emf thereby making commutation spark-less. With interpoles, spark-less commutation can be obtained up to 20 to 30% overload with fixed brush position. In fact, interpoles raise sparking limit of a machine to almost the same value as heating

Interpole of Compoles

- limit. Hence, for a given output, an interpole machine can be made smaller and, therefore, cheaper than a non-interpolar machine.
- As interpoles carry armature current, their commutating emf is proportional to the armature current. This ensures automatic neutralization of reactance voltage which is also due to armature current.
- (ii) Another function of the interpoles is to neutralize the cross-magnetising effect of armature reaction. Hence, brushes are not to be shifted from the original position.





Interpole of Compoles

- OF as before, represents the mmf due to main poles. OA represents the cross-magnetising mmf due to armature. BC which represents mmf due to interpoles, is obviously in opposition to OA, hence they cancel each other out. This cancellation of cross-magnetisation is automatic and for all loads because both are produced by the same armature current.
- The distinction between the interpoles and compensating windings should be clearly understood. Both are connected in series and thier m.m.fs. are such as to neutralize armature reaction. But compoles additionally supply mmf for counteracting the reactance voltage induced in the coil undergoing commutation.
- Moreover, the action of the compoles is localized; they have negligible effect on the armature reaction occurring on the remainder of the armature periphery.

DC MOTOR

Electrical motor: It is a machine which convert electrical energy into mechanical energy.

AC Motor: motor that runs on alternating current (AC) electricity.

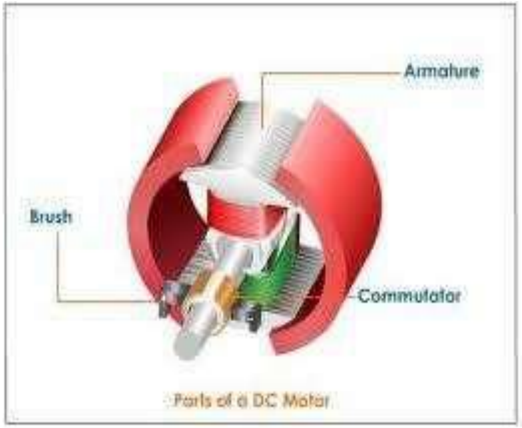
DC Motor: motor that runs on direct current (DC) electricity.

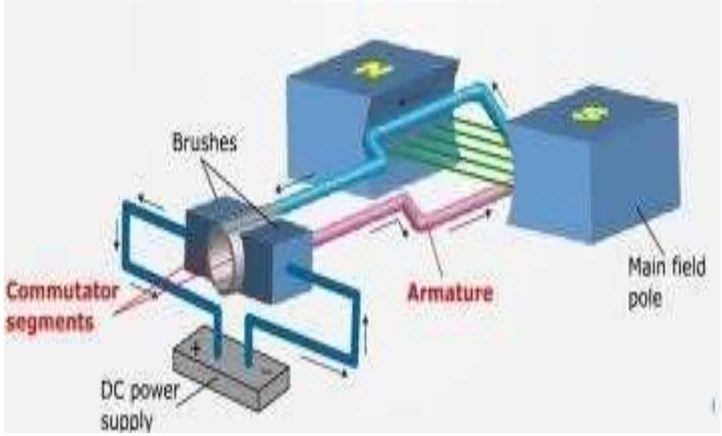
UNIT-III

DC MOTORS

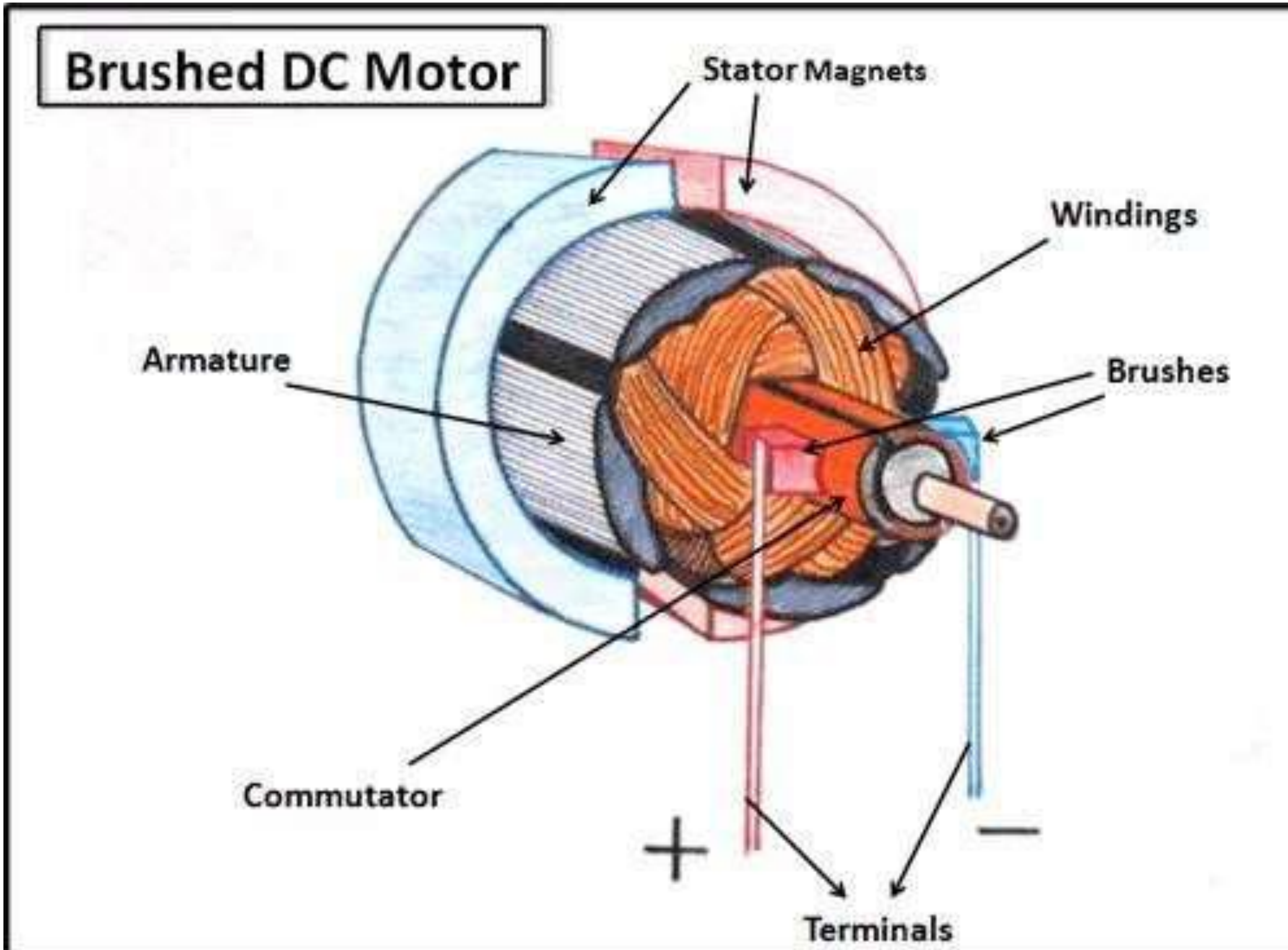
Principle of operation of DC Motor:

When current carrying conductor is placed in a magnetic field it experience a force.

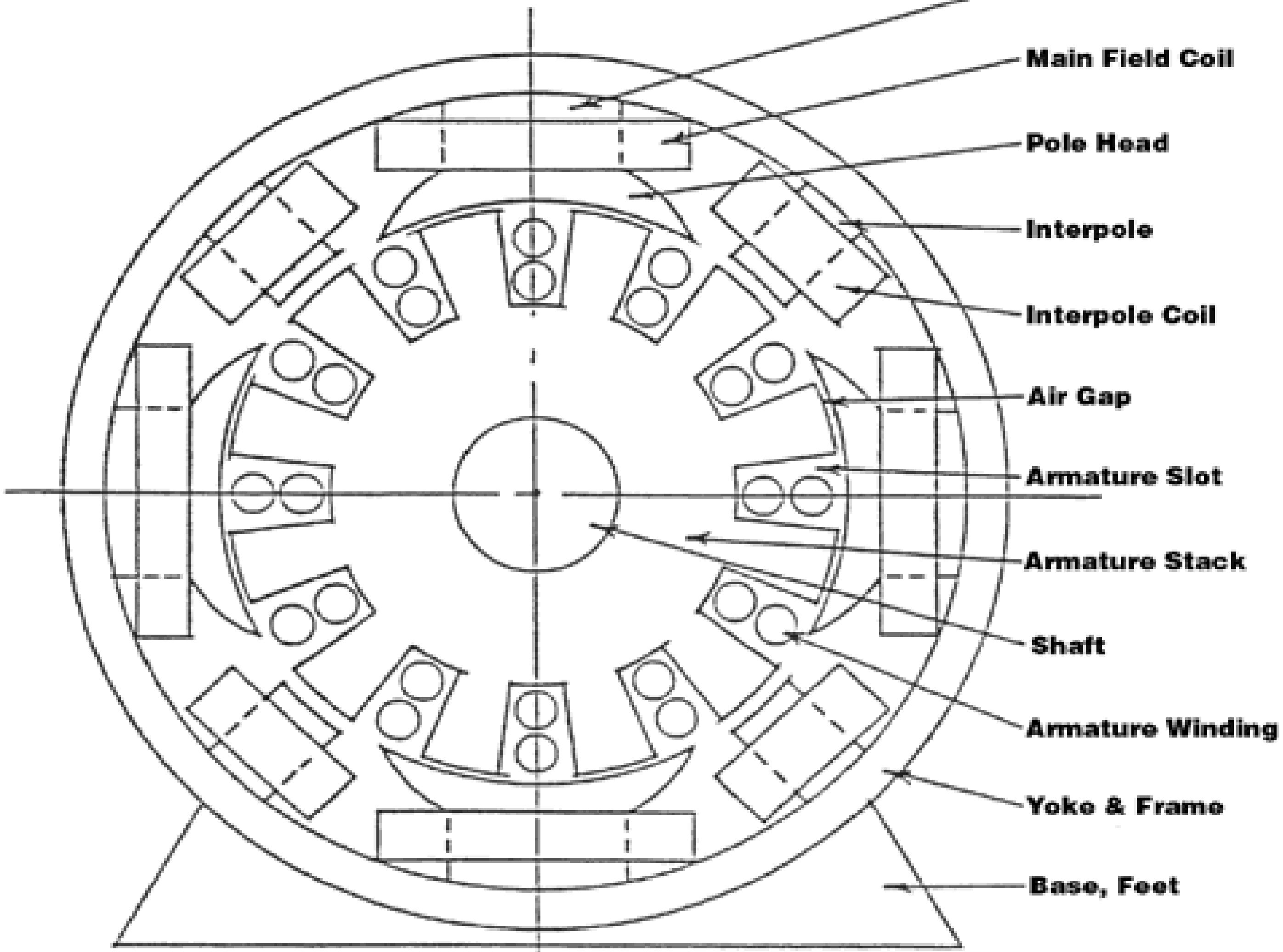




Construction of DC Motor:



Construction of DC Motor:

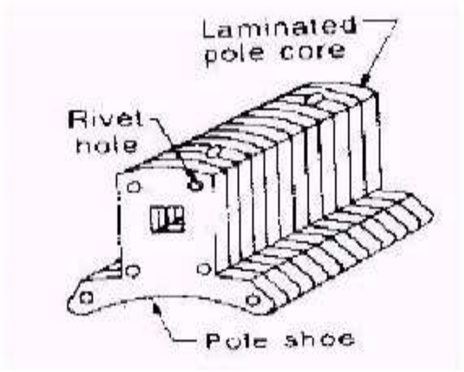


Function of each part of DC Motor:

Yoke:

- It is outer cover of dc motor also called as frame.
- It provides protection to the rotating and other part of the machine from moisture, dust etc.
- Yoke is an iron body which provides the path for the flux to complete the magnetic circuit.
- It provides the mechanical support for the poles.
- Material Used: low reluctance material such as cast iron, silicon steel, rolled steel, cast steel etc.

Poles, and pole core:

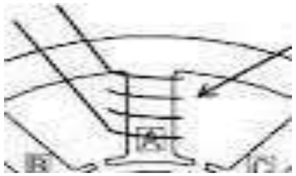


- Poles are electromagnet, the field winding is wound over it.
- It produces the magnetic flux when the field winding is excited.
- The construction of pole is done using the lamination of particular shape to reduce the power loss due to eddy current.

pole shoe:

- Pole shoe is an extended part of a pole. Due to its typical shape, it enlarges the area of the pole, so that more flux can pass through the air gap to armature.
- Material Used: low reluctance magnetic material such as cast steel or cast iron is used for construction of pole and pole shoe.

Field winding:



- The coil wound on the pole core are called field coils.
- Field coils are connected in series to form field winding.
- Current is passed through the field winding in a specific direction, to magnetize the poles and pole shoes. Thus magnetic flux is produce in the air gap between the pole shoe and armature.
- Field winding is also called as Exciting winding.
- Material Used for copper conductor is copper.
- Due to the current flowing through the field winding alternate N and S poles are produced.

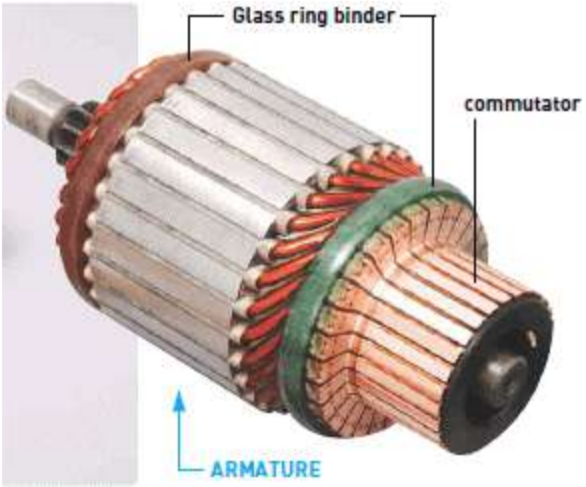
Armature core:

- Armature core is a cylindrical drum mounted on the shaft.
- It is provided with large number of slots all over its periphery and it is parallel to the shaft axis.
- Armature conductors are placed in these slots.
- Armature core provides low reluctance path to the flux produced by the field winding.
- Material used: high permeability, low reluctance cast steel or cast iron material is used.
- Laminated construction of iron core is used to minimize the eddy current losses.

Armature winding:

- Armature conductor is placed in a armature slots present on the periphery of armature core.
- Armature conductor are interconnected to form the armature winding.
- When the armature winding is rotated using a prime mover, it cuts the magnetic flux lines and voltage gets induced in it.
- Armature winding is connected to the external circuit (load) through the commutator and brushes.
- Material Used: Armature winding is suppose to carry the entire load current hence it should be made up of conducting material such as copper.

Commutator:



- It is a cylindrical drum mounted on the shaft along with the armature core.
- It is made up of large number of wedge shaped segments of hard-drawn copper.
- The segments are insulated from each other by thin layer of mica.
- Armature winding are tapped at various points and these tapping are successively connected to various segments of the commutator.

Function of commutator:

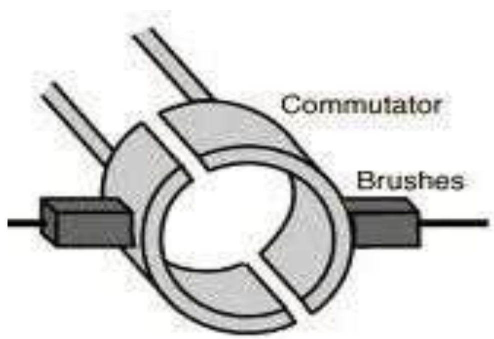
- It converts the ac emf generated internally into dc
- It helps to produce unidirectional torque.

Material Used: it is made up of copper and insulating material between the segments is mica.

Brushes:

- Current are conducted from the armature to the external load by the carbon brushes which are held against the surface of the commutator by springs.
- Function of brushes: To collect the current from the commutator and apply it to the external load in generator, and vice versa in motor.
- Material Used:

Brushes are made of carbon and they are rectangular in shape.



Back emf:

- When the armature winding of dc motor is start rotating in the magnetic flux produced by the field winding, it cuts the lines of magnetic flux and induces the emf in the armature winding.
- According to Lenz's law (*The law that whenever there is an induced electromotive force (emf) in a conductor, it is always in such a direction that the current it would produce would oppose the change which causes the induced emf.*), this induced emf acts in the opposite direction to the armature supply voltage. Hence this emf is called as back emfs.

$$E_b = \frac{N\emptyset Z}{60}\frac{P}{A} \text{ Volts}$$

N= speed in rpm

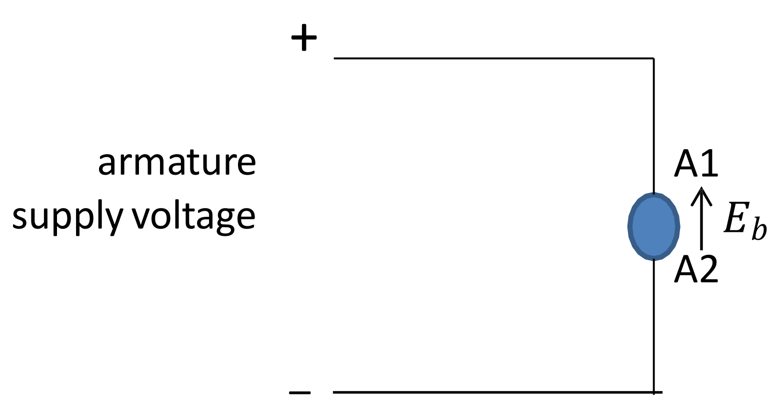
$\emptyset$= flux per pole

Z= no of conductors

P=no of pole pairs

A=area of cross section of conductor

E_b= back emf



Voltage and Power equation of DC Motor:

$$V = Eb + IaRa$$

If we multiply the above equation by Ia, we will get

$$VIa = EbIa + Ia^2Ra$$

$VIa = electrical\ power\ supplied\ to\ the\ motor$
$EbIa = electrical\ equivalent\ of\ the\ mechanical\ power\ produced\ by\ the\ motor$
$Ia^2Ra = power\ loss\ taking\ place\ in\ armature\ winding$
Thus,

$$EbIa = VIa - Ia^2Ra$$

=input power-power loss

thus, $EbIa$= Gross mechanical power produce by the motor

= Pm

Torque equation of DC Motor:

$mec\square anical\ power\ required\ to\ rotate\ t\square e\ s\square aft\ on$

$mec\square anical\ side = T\omega$.. 1

T = Torque in Newton-meter

ω= angular velocity in radian /second

$gross\ mec\square anical\ power\ produce\ by\ t\square e\ motor\ on$

$electrical\ side = EbIa$.. 2

Eb = back emf in volts

Ia = armature current in ampere

equating eqnuation 1 and 2, we get

$$EbIa = T\omega \qquad \text{..} \quad 3$$

$\omega = \frac{2\pi N}{60}$ .... $\left\{ \frac{2\pi N}{60} \right.$ = Speed in rpm

And $Eb = \frac{N\emptyset ZP}{A60}$

Thus, equation (3) become

$$\frac{N\emptyset ZP}{A60} Ia = T \frac{2\pi N}{60}$$

$$T = \frac{P\emptyset ZIa}{2\pi A} = \frac{0.159P\emptyset ZIa}{A} = \left(\frac{0.159PZ}{A}\right) \emptyset Ia$$

P, Z and A are constant, hence we can say

$$T \text{ a } \emptyset Ia$$

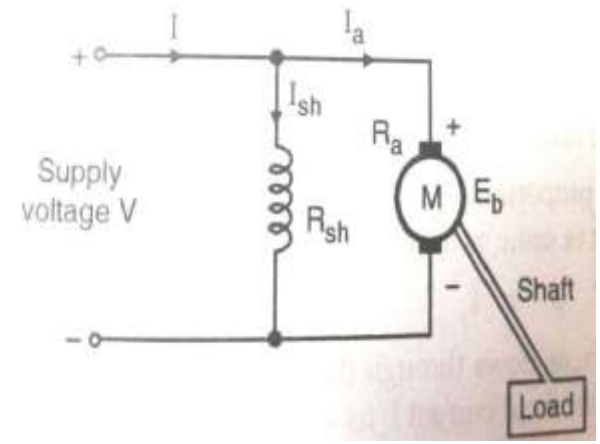
Thus torque produce by the DC Motor is proportional to the main field flux Ø and armature current Ia

Types of DC Motor:

- Classification of the d.c. motor depends on the way of connecting the armature and field winding of a d.c. motor:

1. DC Shunt Motor
2. DC Series Motor
3. DC Compound Motor
    - Short shunt compound
        - Cumulative compound motor
        - Differential compound motor
    - long shunt compound
        - Cumulative compound motor
        - Differential compound motor

DC Shunt Motor:



- In dc shunt motor the armature and field winding are connected in parallel across the supply voltage
- The resistance of the shunt winding R_{sh} is always higher than the armature winding R_a
- Since V and R_{sh} both remains constant the I_{sh} remains essentially constant, as field current is responsible for generation of flux.

  thus $\emptyset$ a I_{sh}
- So shunt motor is also called as constant flux motor.

Torque and Speed equation of DC Shunt Motor:

As we have seen for dc motor

$$T \text{ a } \emptyset Ia$$

But for dc shunt motor :$\emptyset$ a Is□

And Is□ is constant , thus $\emptyset$ is also constant

So torque in dc shunt motor is

$$T \text{ a } Ia$$

For dc motor

$$Eb = \frac{N\emptyset ZP}{A60}$$

Z , $P, A, \emptyset$ and 60 are constants

Thus, $N \text{ a } Eb \text{ a } (V - IaRa)$

Characteristics of DC Shunt Motor:

To study the performance of the DC shunt Motor various types of characteristics are to be studied.

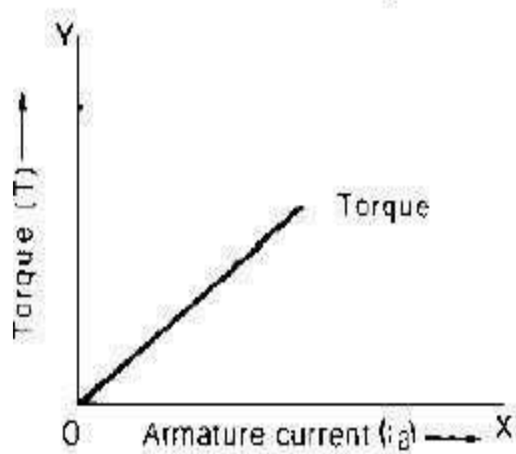
1. Torque Vs Armature current characteristics.
2. Speed Vs Armature current characteristics.
3. Speed Vs Torque characteristics.

Torque Vs Armature current characteristics of DC Shunt motor

This characteristic gives us information that, how torque of machine will vary with armature current, which depends upon load on the motor.

$$T \text{ a } Ia$$

Thus,



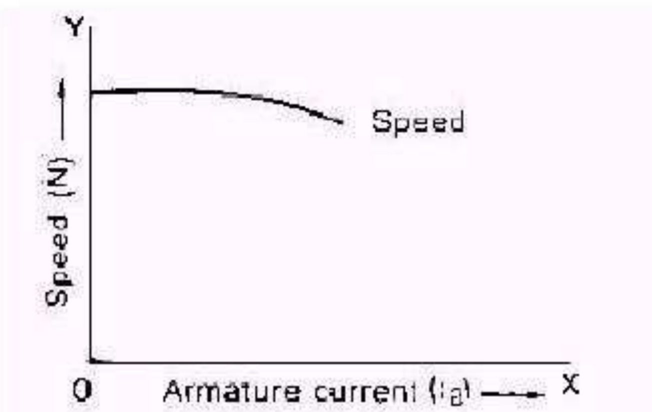
Speed Vs Armature current characteristics of DC Shunt Motor

The back emf of dc motor is $Eb = \frac{N\emptyset ZP}{A60} = V - IaRa$

Therefore $N = \frac{(V - I_a R_a)\ 60\ A}{\phi PZ} = \frac{K(V - I_a R_a)}{\phi}$

where K = 60A/ ZP and it is constant. In dc shunt motor, when supply voltage V is kept constant the shunt field current and hence flux per pole will also be constant.

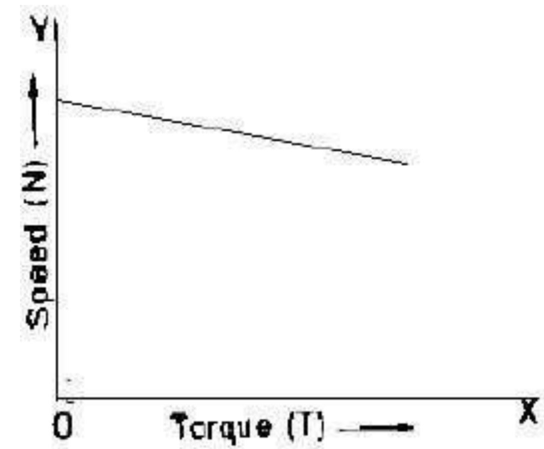
$\therefore N \propto V - Ia\,Ra$



- Therefore shunt motor is considered as constant speed motor.

Speed Vs Torque characteristics of DC Shunt motor

- From the above two characteristics of dc shunt motor, the torque developed and speed at various armature currents of dc shunt motor may be noted.
- If these values are plotted, the graph representing the variation of speed with torque developed is obtained.
- This curve resembles the speed Vs current characteristics as the torque is directly proportional to the armature current.



Applications of DC shunt Motor:

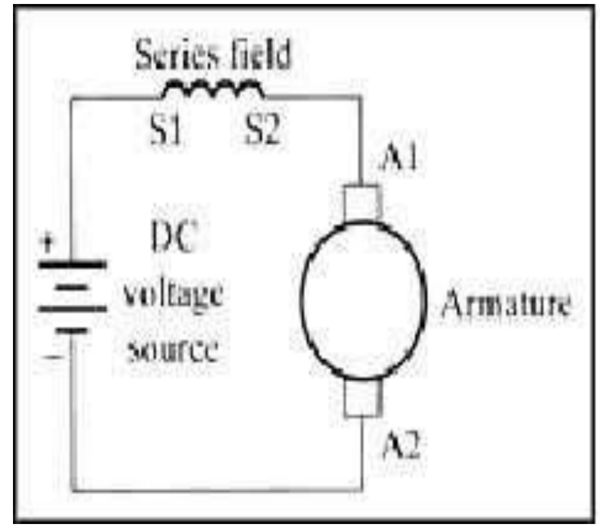
These motors are constant speed motors, hence used in applications requiring constant speed.

Like:

1) Lathe machine
2) Drilling machine
3) Grinders
4) Blowers
5) Compressors

DC Series Motor:

- In this type of DC motor the armature and field windings are connected in series.



- the resistance of the series field winding Rs is much smaller than the armature resistance Ra
- The flux produced is proportional to the field current but in this

  $I_{f=}I_a$ thus Ø a Ia

- Thus flux can never become constant in dc series motor as load changes I_f and I_a also gets changed
- Thus dc series motor is not a constant flux motor.

Torque and Speed equation of DC Series Motor:

As we have seen for dc motor

$$T \text{ a } \emptyset Ia$$

But for dc series motor as $I_{f=}I_a$ $t?us$ Ø a Ia

So torque in dc series motor is

$$T \text{ a } Ia^2$$

For dc motor

$$Eb = \frac{N\emptyset ZP}{A60}$$

Z , P, A and 60 are constants

Thus, N a $\frac{Eb}{\emptyset}$ a $\frac{(V-IaRa)-I_sR_s}{\emptyset} = \frac{V-Ia(Ra+R_s)}{\emptyset}$....... as Ia=I_s

for dc series motor

Characteristics of DC Series Motor:

To study the performance of the DC series Motor various types of characteristics are to be studied.

1. Torque Vs Armature current characteristics.
2. Speed Vs Armature current characteristics.
3. Speed Vs Torque characteristics

Torque Vs Armature current characteristics of DC Series motor

- Torque developed in any dc motor is

$$T \text{ a } \emptyset Ia$$

- In case of a D.C. series motor, as field current is equal to armature current, and for small value of I_a

$$\emptyset \text{ a } I_a$$

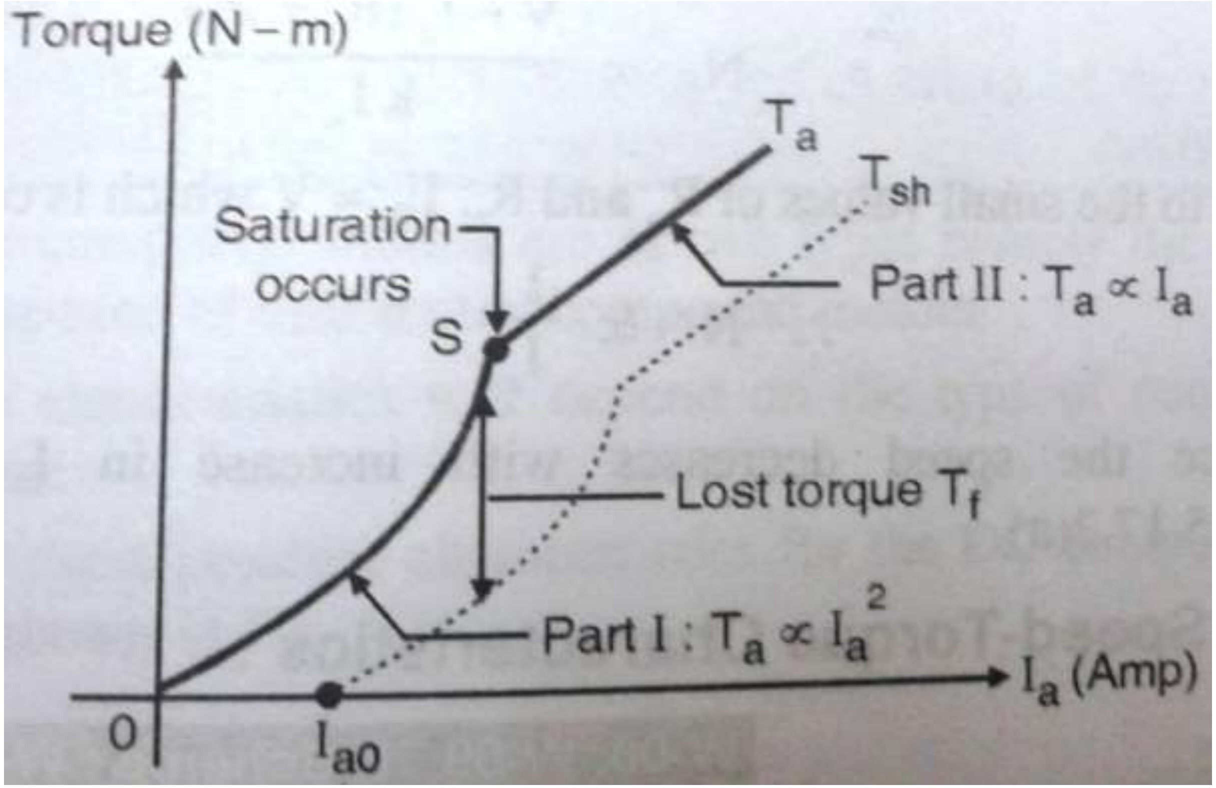
- Therefore the torque in the dc series motor for small value of I_a

$$T \text{ a } Ia^2$$

- When I_a is large the Ø remains the constant due to saturation, thus torque is directly proportional to armature current for large value of I_a

$$T \text{ a } I_a$$

- Thus Torque Vs Armature current characteristics begin to raise parabolically at low value of armature current and when saturation is reached it become a straight line as shown below.



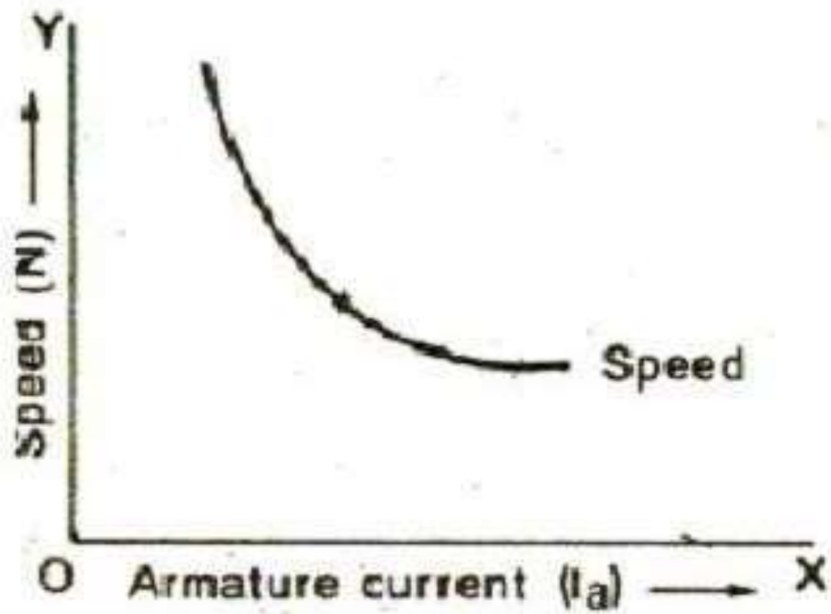
Speed Vs Armature current characteristics of DC Series Motor

Consider the following equation:

$$N = \frac{K(V - IaRa)}{\emptyset}$$

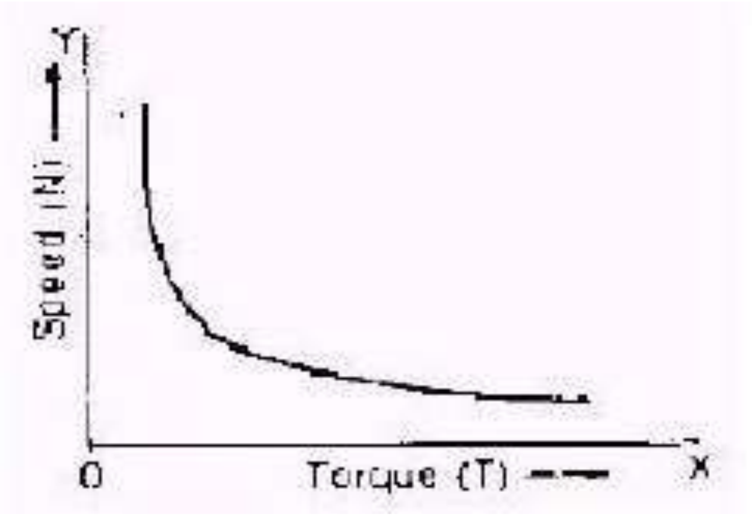
- When supply voltage V is kept constant, speed of the motor will be inversely proportional to flux.
- In dc series motor field exciting current is equal to armature current which is nothing but a load current.
- Therefore at light load when saturation is not attained, flux will be proportional to the armature current and hence speed will be inversely proportional to armature current.
- Hence speed and armature current characteristics is hyperbolic curve upto saturation.

- As the load increases the armature current increases and field gets saturated, once the field gets saturated flux will become constant irrespective of increases in the armature current. Therefore at heavy load the speed of the dc series motor remains constant.
- This type of dc series motor has high starting torque.



Speed Vs Torque characteristics of DC Series motor

- The Speed Vs Torque characteristics of dc series motor will be similar to the Speed Vs Armature current characteristics it will be rectangular hyperbola, as shown in the fig.



Applications of DC series Motor-

These motors are useful in applications where starting torque required is high and quick acceleration. Like:

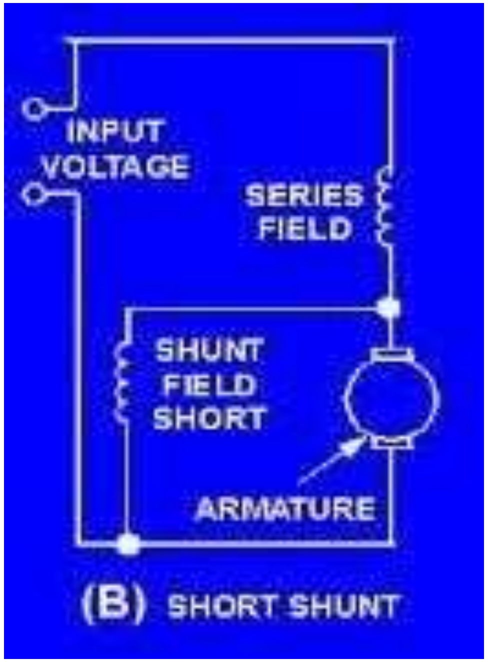
1) Traction
2) Hoists and Lifts
3) Crane
4) Rolling mills
5) Conveyors

DC Compound Motor:

- The DC compound motor is a combination of the series motor and the shunt motor. It has a series field winding that is connected in series with the armature and a shunt field that is in parallel with the armature.
- The combination of series and shunt winding allows the motor to have the torque characteristics of the series motor and the regulated speed characteristics of the shunt motor. Several versions of the compound motor are:
- Short shunt Compound Motors
- Long shunt Compound Motors

Short shunt compound motor:

- When shunt field winding is connected in parallel with armature like dc shunt motor and this assembly is connected in series with the series field winding then this type of motor is called as short shunt compound motor.

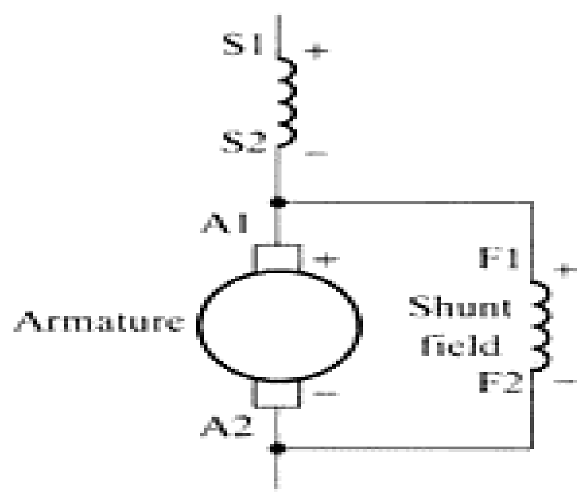


- Depending on the polarity of the connection short shunt motor is classified as:

1. Cumulative compound motor.
2. Differential compound motor.

Cumulative compound motor (short shunt):

- Figure shows a diagram of the cumulative compound motor. It is so called because the shunt field is connected so that its coils are aiding the magnetic fields of the series field and armature.
- In this figure that the top of the shunt field is positive polarity and that it is connected to the positive terminal of the armature.



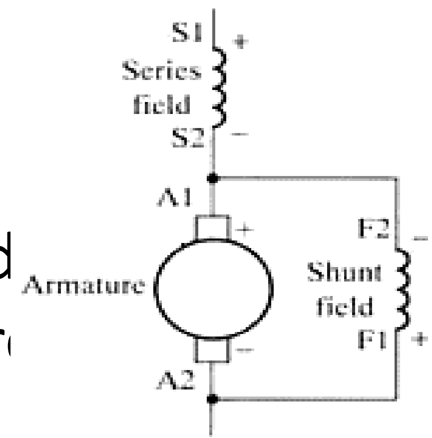
(a) Cummulative compound dc motor (short shunt)

Cumulative compound motor (short shunt):

- The cumulative compound motor is one of the most common DC motors because it provides high starting torque and good speed regulation at high speeds.
- Since the shunt field is wired with similar polarity in parallel with the magnetic field aiding the series field and armature field, it is called cumulative.
- When the motor is connected this way, it can start even with a large load and then operate smoothly when the load varies slightly.

Differential Compound Motor (short shunt):

Figure shows the diagram for a differential compound motor with the shunt field connected so its polarity is reversed to the polarity of the armature. Since the shunt field connected in parallel with only the armatur considered a short shunt.



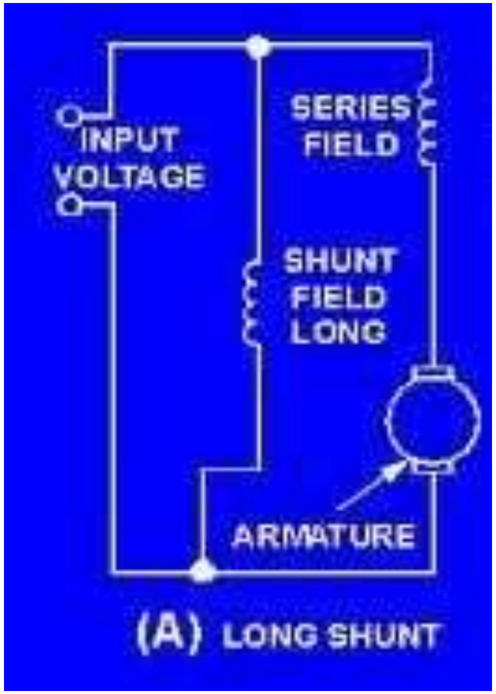
(b) Differential compound dc motor (short shunt)

Differential Compound Motor (short shunt):

- In the differential compound motor the shunt field is connected so that its magnetic field opposes the magnetic fields in the armature and series field.
- When the shunt field's polarity is reversed like this, its field will oppose the other fields and the characteristics of the shunt motor are not as pronounced in this motor.
- This means that the motor will tend to overspeed when the load is reduced just like a series motor. Its speed will also drop more than the cumulative compound motor when the load increases at full rpm.
- These two characteristics make the differential motor less desirable than the cumulative motor for most applications.

Long shunt compound motor:

- when the shunt field is connected in parallel with both the series field and the armature then this type of motor is called as long shunt compound motor.



- Depending on the polarity of connection of shunt field winding, series field winding and armature, long shunt motor is classified as:

1. Cumulative Compound Motor.
2. Differential Compound Motor.

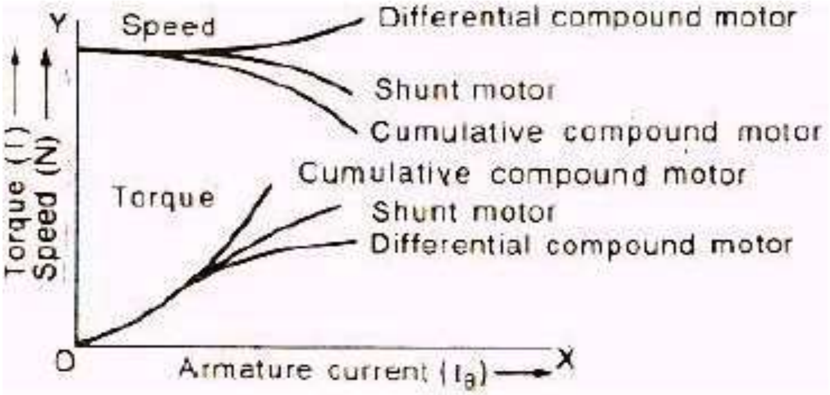
Characteristics of DC compound Motor:

To study the performance of the DC compound Motor various types of characteristics are to be studied.

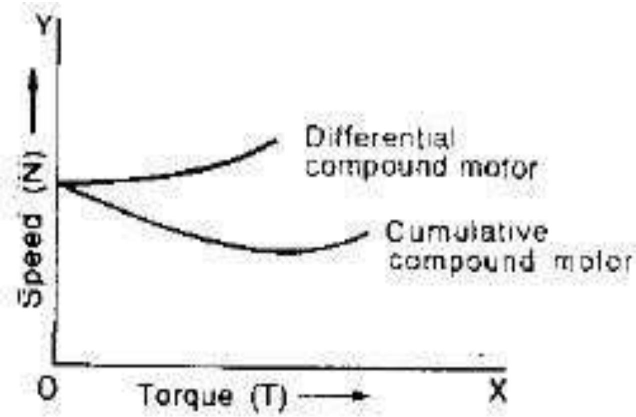
1. Torque Vs Armature current characteristics.
2. Speed Vs Armature current characteristics.
3. Speed Vs Torque characteristics

- In dc compound motors both shunt and series field acting simultaneously.
- In cumulative compound motor series field assist the shunt field.
- In such motors when armature current increases the field flux increases.
- So for given armature current the torque developed will be greater and speed lower when compared to a dc shun motor.
- In differential compound motor series field opposes the shunt field, therefore when armature current decreases the field flux decreases, so for given armature current the torque developed will be lower and speed greater when compare to the dc shunt motor.

Torque Vs Armature current and Speed Vs Armature current characteristics of dc compound motors



Speed Vs Torque characteristics are compared with that of shunt motor.



Applications of DC Compound Motor

CUMULATIVE COMPOUND MOTOR:

- These motors have high starting torque.
- They can be operated even at no loads as they run at a moderately high speed at no load.
- Hence cumulative compound motors are used for the following applications.

1. Elevators
2. Rolling mills
3. Punches
4. Shears
5. planers

Applications of DC Compound Motor

Differential Compound Motor:

- The speed of these motors increases with increases in the load which leads to an unstable operation.
- Therefore we can not use this motor for any practical applications.

Speed Control of DC Motor:

- The speed equation of dc motor is

$$N \text{ a } \frac{Eb}{\emptyset} \text{ a } \frac{(V - IaRa)}{\emptyset}$$

- But the resistance of armature winding or series field winding in dc series motor are small.
- Therefore the voltage drop $IaRa$ or $Ia(Ra + R_s)$ across them will be negligible as compare to the external supply voltage V in above equation.
- Therefore $N \text{ a } \frac{V}{\emptyset}$, since V>>>> $IaRa$
- Thus we can say

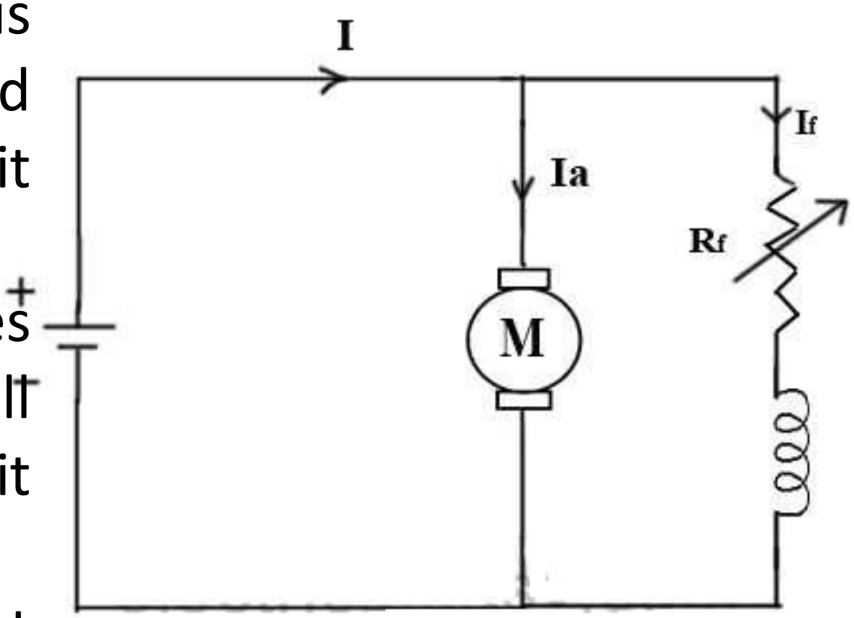
1. Speed is inversely proportional to flux Ø.
2. Speed is directly proportional to armature voltage.
3. Speed is directly proportional to applied voltage V.

So by varying one of these parameters, it is possible to change the speed of a dc motor

SPEED CONTROL METHODS OF DC SHUNT MOTOR

1.Flux Control Method:

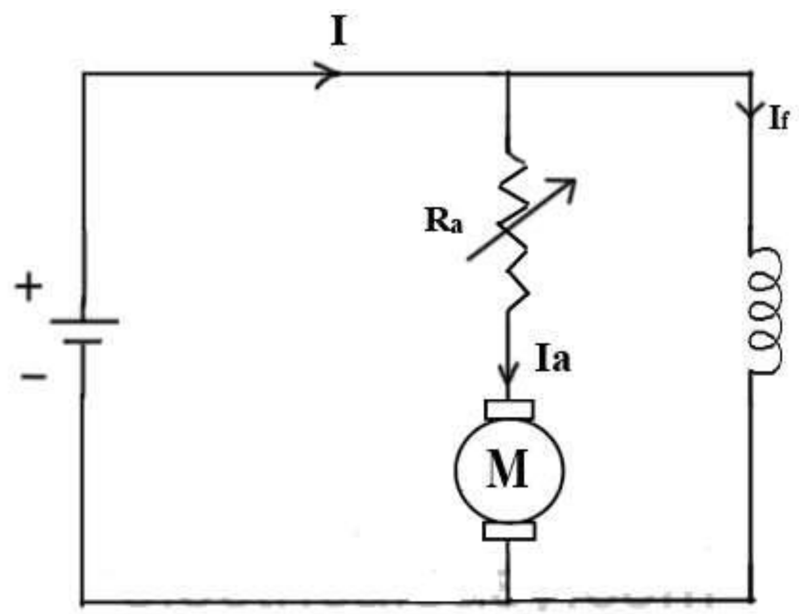
- To control the flux, a rheostat is added in series with the field winding, as shown in the circuit diagram.
- Adding more resistance in series with the field winding will increase the speed as it decreases the flux.
- In shunt motors, as field current is relatively very small, I_{sh}^2R loss is small. Therefore, this method is quite efficient.



SPEED CONTROL METHODS OF DC SHUNT MOTOR

2.Armature Control Method:

- **Speed of a dc motor** is directly proportional to the back emf E_b and $E_b = V - I_aR_a$.
- That means, when supply voltage V and the armature resistance R_a are kept constant, then the speed is directly proportional to armature current I_a.
- Thus, if we add resistance in series with the armature, I_a decreases and, hence, the speed also decreases.
- Greater the resistance in series with the armature, greater the decrease in speed.



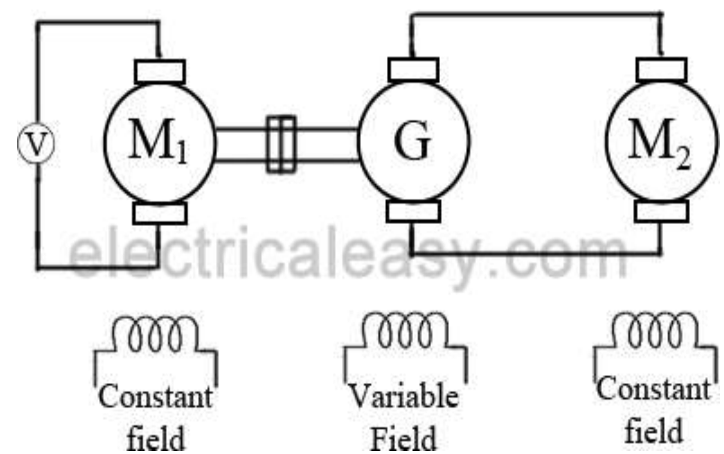
3. Voltage Control Method

a) Multiple voltage control:

In this method, the shunt field is connected to a fixed exciting voltage and armature is supplied with different voltages. Voltage across armature is changed with the help of a suitable switchgear.

b) Ward-Leonard System:

This system is used where very sensitive **speed control of motor** is required (e.g electric excavators, elevators etc.). The arrangement of this system is as shown in the figure at right.



M_2 is the motor whose speed control is required.

M_1 may be any AC motor or DC motor with constant speed.

G is a generator directly coupled to M_1.

Speed Control Of Series Motor

1. Flux Control Method

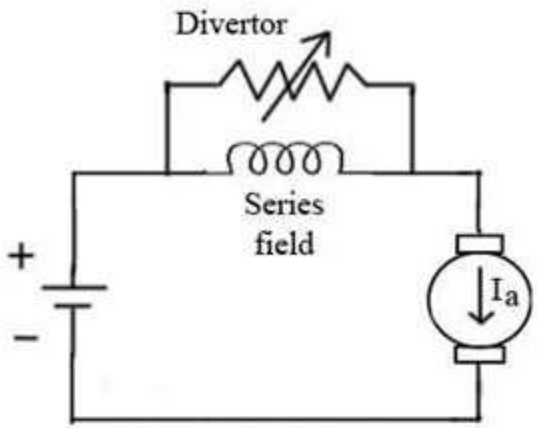


fig (a) Field Divertor

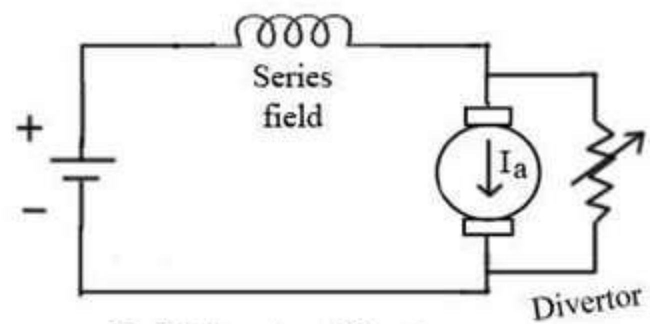


fig (b) Armature Divertor

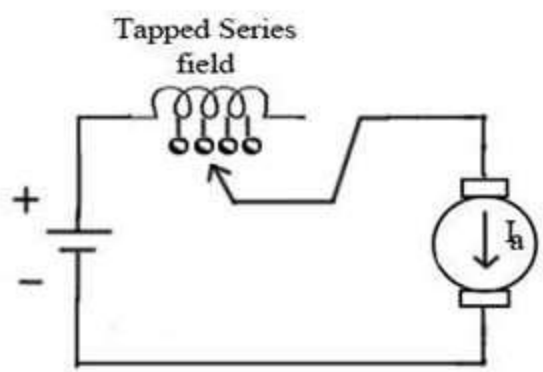


fig (c) Tapped field

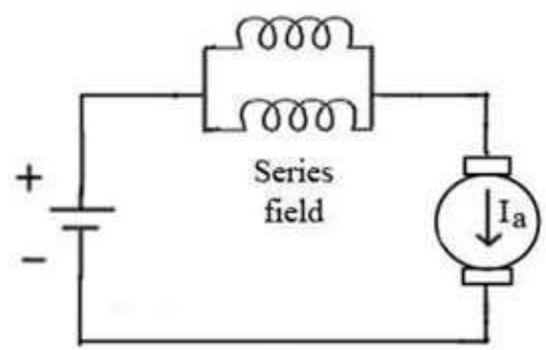


fig (d) Paralleling Field coils

2. Variable Resistance In Series With Armature

By introducing a resistance in series with the armature, voltage across the armature can be reduced. And, hence, speed reduces in proportion with it.

3. Series-Parallel Control

This system is widely used in electric traction, where two or more mechanically coupled series motors are employed. For low speeds, the motors are connected in series, and for higher speeds the motors are connected in parallel.

When in series, the motors have the same current passing through them, although voltage across each motor is divided. When in parallel, the voltage across each motor is same although the current gets divided.

Reversal of Direction of Rotation

- The direction of the magnetic flux in the air gap depends on the direction of the field current.
- And the direction of the force exerted on the armature winding depends on the direction of flux and the direction of armature current.
- Thus in order to reverse the direction of dc motor, we have to reverse the direction of force.
- This can be achieved either by changing the terminals of the armature or the terminals of the field winding.

Need of Starter

We know that, $V = E_b + I_a R_a$............for a dc shunt motor

and $V = E_b + I_a(R_a + R_s)$....for a dc series motor

Hence the expression for I_a are as follows:

$$I_a = \frac{V - E_b}{R_a}$$ .... for dc shunt motor

$$I_a = \frac{V - E_b}{(R_a + R_s)}$$ ....for dc series motor

At the time of starting the motor, speed N=0 and hence the back emf E_b=0. Hence the armature current at the time of starting is given by,

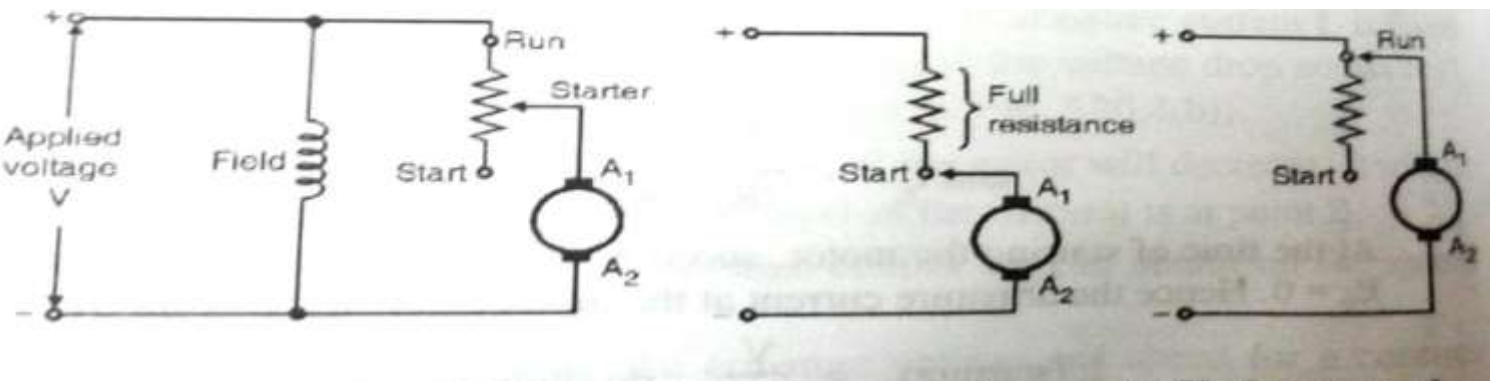
$$I_{a(starting)} = \frac{V}{R_a}$$ ....for dc shunt motor

$$I_{a(starting)} = \frac{V}{(R_a + R_s)}$$ ......for dc series motor

- Since the the values of R_a *and* R_s are small, the starting currents will be tremendously large if the rated voltage is applied at the time of starting.
- The starting current of the motor can be 15 to 20 times higher than the full load current.
- Due to high starting current the supply voltage will fluctuate.
- Due to excessive current, the insulation of the armature winding may burn.
- The fuses will blow and circuit breakers will trip.
- For dc series motors the torque T a $I_a{}^2$. So an excessive large starting torque is produced. This can put a heavy mechanical stress on the winding and shaft of the motor resulting in the mechanical damage to the motor.
- So to avoid all these effects we have to keep the starting current of motor below safe limit. This is achieved by using starter.

Principle of starter:

- Starter is basically a resistance which is connected in series with the armature winding only at the time of starting the motor to limit the starting current.
- The starter of starter resistance will remain in the circuit only at the time of starting and will go out of the circuit or become ineffective when the motor speed upto a desire speed.



(a) Principle of starter (b) At the time of starting (c) Under normal operating condition

- At the time of starting, the starter is in the start position as shown in fig. so the full starter resistance appears in series with the armature. This will reduce the starting current.
- The starter resistance is then gradually cut off. The motor will speed up, back emf will be developed and it will regulate the armature current. The starter is not necessary then.
- Thus starter is pushed to the Run position as shown in fig under the normal operating condition. The value of starter resistance is zero in this position and it does not affect the normal operation.

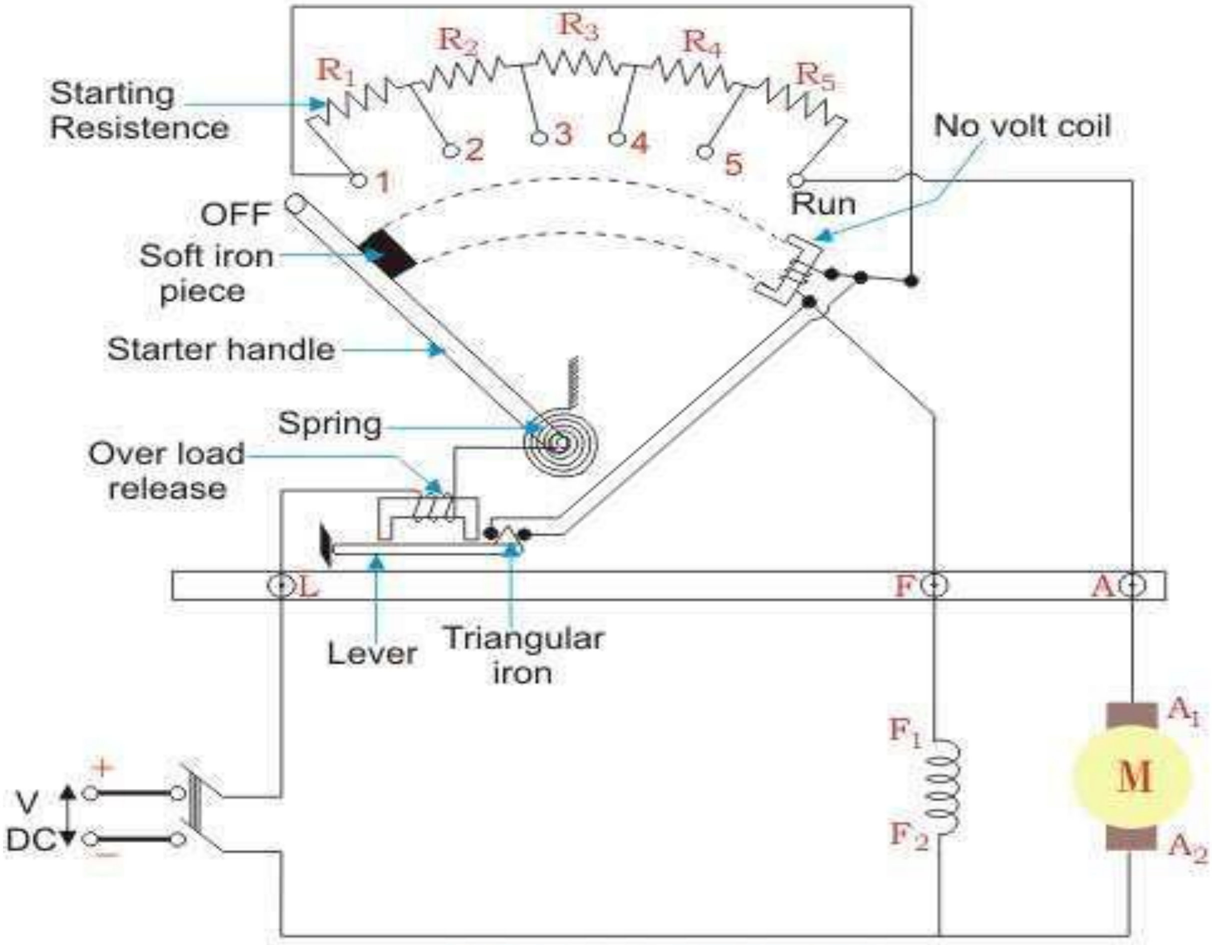
Types of starter:

1. Three point starter
2. Four point starter

Three Point Starter

- A **3 point starter** is a device that helps in the starting and running of a DC shunt motor or compound wound DC motor .
- To limit the starting current to acceptably low value.

Construction and working of three-point starter



Three Point Starter

- Construction wise a starter is a variable resistance, integrated into the number of sections as shown in the figure beside. The contact points of these sections are called studs and are shown separately as **OFF, 1, 2, 3, 4, 5, RUN**. Other than that there are three main points, referred to as

1. 'L' -Line terminal (Connected to positive of supply)
2. 'A' -Armature terminal (Connected to the armature winding)
3. 'F'- Field terminal (Connected to the field winding)

The starter handle is now moved from stud to stud, and this builds up the speed of the motor until it reaches the **RUN** position. The Studs are the contact point of the resistance. In the RUN position, three main points are considered. They are as follows.

- The motor attains the full speed.
- The supply is direct across both the windings of the motor.
- The resistance R is completely cut out.
- The handle H is held in RUN position by an electromagnet energised by a **no volt trip coil (NVC)**.
- The no voltage coil also provides protection against an open circuit in the field windings. The other protective device incorporated in the starter is the overload protection.
- The **Over Load Trip Coil (OLC)** provide the overload protection of the motor. The overload coil is made up of a small electromagnet, which carries the armature current.

Drawbacks of a 3 Point Starter

- The 3 point starter suffers from a serious drawback for motors with a large variation of speed by adjustment of the field rheostat.

- To increase the speed of the motor, the field resistance should be increased. Therefore, the current through the shunt field is reduced.

- The field current may become very low because of the addition of high resistance to obtain a high speed.

APPLICATIONS OF DC MOTORS

MOTORS..	APPLICATIONS...
D.C. SHUNT MOTOR	LATHES , FANS, PUMPS DISC AND BAND SAW DRIVE REQUIRING MODERATE TORQUES.
D.C. SERIES MOTOR	ELECTRIC TRACTION, HIGH SPEED TOOLS
D.C. COMPOUND MOTOR	ROLLING MILLS AND OTHER LOADS REQUIRING LARGE MOMENTARY TORQUES.